Assessing the Thermal Performance of Glazed Curtain Wall Systems

S+G Project Case Study

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ABSTRACT

The improvement of curtain wall thermal performances and the optimisation of the issues connected with this technology can lead to a sensible reduction of the energy consumption of the building as well as to an increase level of occupant comfort and longer durability of the façade.

The aim of this work is to improve the curtain wall technology especially as far as the connection between the glass and the frame is concerned, since it is the part that mainly affects the performances of the whole façade. This project focuses on the different aspects of the thermal performance of curtain wall systems in order to achieve a higher thermal performance, meeting the objectives of lowering energy demand, improving durability and enhancing indoor comfort.

In order to develop new high performance curtain wall connections and to test their level of performance compared with the state of the art ones, two methods were deployed: a numerical and an experimental one. FEM analysis was performed with the software THERM (LBNL) analysing the profile of surface temperatures and the U-values of the details. In the FEM analysis, different materials and geometries were studied. The experimental characterisation of the thermal energy performance of the studied design options was performed by means of thermometric measurements in a climatic cell. The purpose of the experimental analysis was the verification of the effective improvement of the performance in the new details and the comparison with the simulation, aiming at the validation of the simulation model.
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1. INTRODUCTION

Curtain walling (CW) is a system of vertical building enclosure which supports no load other than its own weight and the environment loads which act upon it (i.e. wind, water...). This system is being widely adopted in high-rise buildings because of its lightness and good exterior appearance [1]. The system mainly consists of mullion materials and infill units that are selected and designed to achieve the desired structural, thermal and day lighting performances as well as to meet cost and aesthetic requirements. Curtain walls have to satisfy different requirements [2]:

- Wind loads resistance, including pressure variations over the various elements of the curtain walls’ exterior surface.
- Accommodating movements (that could be caused by thermal or moisture variations) without any reduction in performances.
- Prevention of unwanted air flow from the exterior to the interior surface maintaining the occupant comfort, limiting heat loss and reducing wind noise.
- Resistance to water penetration, specifically preventing water from penetrating into those parts that would be adversely affected by the presence of water (i.e. insulation materials and sealed transparent cavities).
- Durability of the components, in particular of all the framing components and of the sealants which are extremely sensitive to moisture and high temperatures.

Particular attention should be paid to the thermal aspect as many defects can be connected to poor thermal performance or poor resistance to thermal loads. Discomfort of the occupants can be caused by draft risk that is due to the air flow generated by the temperature difference between frame (lower) and centre of glazing [3]. The durability of components like adhesives can be compromised due to high temperatures and to condensation that may lead to degradation of performance and damage [4]. The total U-value of the façade and consequently the energy consumption is influenced by the total U-value of the curtain wall system, thus by the U-value of the frame itself, indeed there is still a significant difference between the centre of the glazing performance (lowest centre-of-glass $U_g$ values found are as low as 0.28 W/m$^2$K, while standard values for heating dominated climate ranges now between 0.7 and 1.6 W/m$^2$K) and frame performances (lowest frame $U$-value is currently as low as 0.61 W/m$^2$K and the common value for aluminium frame is 2 W/m$^2$K) [5]. The presence of thermal bridges especially in correspondence of the connection between glazing and frame is one of the main factors that decrease the thermal performance of the whole system (leading for example to internal surface condensation). The connection is in fact believed to be the weakest part of the CW construction from a thermal point of view as far as the thermal performance of the system is
concerned, as it is the interface between different materials and for the fabrication itself. From the fabrication point of view the box-framed curtain wall can be assembled in two different ways: as a unitised system (panels assembled together during fabrication) or as a stick system (components parts assembled on site) [6]. The improvement of CW frame performances and the optimisation of the issues connected with this technology can lead to a sensible reduction of the energy consumption of the building as well as to an increasing comfort of the occupants and greater durability of the façade.

**Aims**

The aim of this work is to improve the curtain wall technology especially as far as the connection between the glass and the frame is concerned since, for the reason previously explained, this is the part that mainly affects the performances of the whole façade. Listed above there are many requirements that a curtain wall system needs to satisfy and some issues that could be improved. This project will focus on the different aspects of the thermal performance (i.e. U-values, surface temperatures, condensation, thermal stresses etc…) in order to achieve higher performance of the curtain wall system. The aim is to meet the objectives of lowering energy demand, improving durability and enhancing comfort. In order to increase the overall thermal performance of curtain walls the following aspects should be addressed:

- Lower U-values of the whole module, therefore decreasing thermal bridge effects between glass and supporting structure;
- Increase the internal surface temperature in order to avoid condensation and the possibility of draft risk, otherwise leading to a decreasing comfort level of the occupants;
- Appropriate temperature of the frame components, as an increasing temperature can compromise the performance and durability of some of the components (i.e. adhesives, primary and secondary sealant etc..), while for special applications, such as double skin façades, too high or too low temperatures in the frame can affect the temperature of the inlet air in the air cavity compromising the overall thermal performance;
- Control of the differential thermal deformation that can occur between frame and glass.

This project will include a study on state-of-the-art curtain wall systems to show how all these issues have been addressed by researches and manufacturer. Some effective design details, in terms of different geometries and novel materials, will be analysed in order to understand the techniques that have been used until now to solve the issues related to the connection between glass and frame.
Method

The purpose of this project is to evaluate the best performance of today’s products and to improve the thermal performance of innovative CW systems. In order to increase the thermal performance of the curtain wall systems the following aspects will be varied in the analysis:

- Materials: the conductivity of materials and their water tightness are among the main factors influencing the overall thermal result. The analysis of novel materials will be carried out for different components such as frames, adhesives, sealant and spacers;
- Geometry of frames: the introduction of cavities in the frame or increased percentage of matt surface can sensibly change the performance of the whole façade [7];
- Position of frames: possible innovative solutions can be a) sealing the frame with the glazing internally adopting new adhesives or b) to include the frame in the Insulated Glazing Unit.

These new details shall not only address thermal performance requirements, but shall be aimed to achieve at least the same level of performance, or beyond, in all the other aspects.

In order to develop high performance curtain wall connections and to test their level of performance compared with the state of the art ones, two methods will be deployed: a numerical and an experimental one. FEM analysis will be performed with the software THERM [8] analysing the profile of temperatures and the U-values of the details. The purpose of the experimental analysis will be the verification of the effective improvement of the performance in the new details and the comparison with the simulation. Furthermore the experimental analysis will be employed as an attempt at developing a technique to survey the thermal performance of CW systems, during their service life.
2. LITERATURE REVIEW

2.1 Curtain Wall performances

Metal curtain walls are widely used in the building industry and offer many advantages including saved space required for the façade, high quality in manufacturing, light weight, significant aesthetic freedom and rapid construction. From a general standpoint, they also exhibit a considerable number of design strengths. They are easy to customize, are available with a variety of interior and exterior aesthetic appearances, and allow a virtually unlimited range of installation locations, configurations and opportunities. Expectations of today's curtain walls exceed the basic functions of providing natural lighting and protecting the interior from environmental effects such as wind and rain. Curtain wall systems are expected to conserve energy and to provide occupant comfort by controlling heat flow and solar radiation [9].

2.2 Thermal performances

The energy consumption of buildings is responsible for approximately 40% of energy used in the developed countries. Glass façades are typically responsible for a large fraction of the heat loss in buildings [10]. Metal curtain walls are still weak assemblies from the thermal point of view, due to the high conductivity of metal and glass, and require further development in order to increase their thermal performance. In practice, metal curtain walls are referred to as “heat sink” in heating-dominant climates. The relatively low thermal resistance results in low surface temperatures in winter and thus may cause condensation and thermal discomfort problems in addition to high energy consumption [3]. The recent requirement for energy conservation and improved indoor thermal comfort means improvements at their performance. Initially, the metal curtain wall industry grew within the metal window industry, and standards developed for windows are also used to evaluate the performance of curtain walls. However, the heat flow through curtain walls is more complex than in windows and depends to a great extent on the design details [11].

The thermal properties of the curtain wall systems shall be selected in order to achieve the following main objectives [2]:
- A reduction in the energy consumption of the building by controlling the heat flow through the façade (measurable in terms of U-values [W/m²·K] and Ψ-values [W/mK]);
- Avoidance of condensation by ensuring the surface temperature higher than the dew point.
2.2.1 U-values

U-value [W/m²K] is a measure of heat loss (W) for a given wall area (m²) at a given temperature differential (K) under fixed environmental conditions consisting of indoor air temperature, outdoor air temperature, and outdoor wind speed. The U-value can be determined in the case of constant boundary conditions (steady state) and one dimensional heat flow. Determining heat loss requires area weighting three components of a curtain wall area: the centre of glass (or centre of panel), the edge of glass (panel), and the frame [12]. Metal and glass are materials which inherently have low resistance to heat flow, but with proper attention to details metal curtain walls can be designed to provide good thermal performance. Generally this is accomplished by minimizing the proportion of metal framing members exposed to the outdoors, trying to decrease the effect of the thermal bridge.

2.2.2 ψ-values, χ-values

A thermal bridge is an area of the building fabric that has a higher thermal transmission than the surrounding parts of the fabric (caused by two-dimensional heat flow, due to change in material and geometry), resulting in a reduction in the overall thermal insulation of the structure. It occurs when materials that have a much higher thermal conductivity than the surrounding material (i.e. they are poorer thermal insulators) penetrate the thermal envelope or where there are discontinuities in the thermal envelope. Heat then flows through the path created, from the warm space (inside) to the cold space (outside) [13]. Because curtain wall frames are usually made of highly conductive metal, and typically go from the exterior of the building through to the interior, thermal bridges will occur [14]. The thermal bridge effect is measured by the ψ-value [W/mK] in case of two dimensional heat flow and by the χ-value [W/K] in case of three-dimensional heat flow.

2.2.3 Condensation Risks

Condensation is water accumulating on cold surfaces, due to the fact that they drop below the dew point temperature of the interior air, which depends on room temperature and relative humidity. Dew point temperatures can be obtained from psychometric charts or from the following approximate formula [15):

\[
T_{dp} = \left(\frac{\varphi}{100}\right)^{1/8} \cdot (112 + 0.9 \, T) + 0.1 \, T - 112
\]  

(2.1)

Where \( \varphi \) is the relative humidity and \( T \) is the indoor air temperature (dry bulb).
Indoor condensation can lead to mould with related health issues, stain and damage to the interior finishes, such as drywall and ceiling tiles, and can cause corrosion in metals. Because of the high conductivity of the metal framing members, frame and edge of glass areas allow high heat loss (U-value). Therefore they can present the lowest internal surface temperatures in the components. As a result, condensation, if any, generally will occur on framing members and edge of glass.

2.2.4 Thermal Stress

The service temperature of CW components can be affected by solar radiation which depends on the orientation of the surface and the location of the building. The durability of components like adhesives can be compromised due to high temperatures that may lead to degradation of performance and damage [4]. Moreover a high temperature difference inside the glazing could lead to differential thermal deformation in the glass itself compromising the structural performance of the glazing unit [16]. Differential temperatures between the inside and the outside can lead to a breakdown in the bond between components of composite panels [2].

2.3 State of the Art Details

Understanding the basic concepts of curtain walls, the design considerations beyond the varying curtain wall types, and the performance requirements for curtain wall systems is crucial for the improvement of the system itself. Curtain walls are classified by their method of fabrication and installation in two categories: stick built and unitized systems (Figure 2.1).

Stick systems consist of curtain wall vertical frame members (mullions), horizontal frame members (transoms) and glass or opaque panels that are installed and connected piece by piece on site. These parts are usually fabricated and shipped to the job site for installation. In larger areas of stick-framed curtain walls, split vertical mullions are sometimes used to allow for thermal movement, which can slightly distort the anchors. In this case, glass units must accommodate movement of the surrounding frame by sliding along glazing gaskets. This movement within the frame and in the anchors tends to induce additional stress on stick built systems. Unitized curtain wall systems are comprised of large units that are assembled and glazed in the factory. They are then shipped to the job site and erected on the building façade. The vertical and horizontal modules mate and stack together to create a complete system. Cranes are most often used to install these systems as modules can be one story tall and 1.5 to 1.8 meters wide [17].
The way glazing is retained by the framing has a visual effect on curtain wall’s appearance and provides a degree of creative freedom for the architects. Two methods, called capped systems and structural silicone glazed systems, use distinctly different means of glazing retention (Figure 2.2). Capped systems physically hold the glazing infill with extrusions (usually in aluminium), combined with rubber glazing gaskets, to lock it to the frame. From the outside the glazing appears to have a picture frame of painted or anodized metal around it (Figure 2.3a). There are variations of capped systems where all four sides can be captured, called four-sided captured systems. The profile of the cap can be any shape possible within the limits of the metal extruding process.

Structural silicone glazed (SSG) systems employ structural silicone sealants that glue the glazing to the frame. Structural silicone sealants have been engineered to create a safe and reliable product for this specific application. The visual difference is a cleaner, uncluttered appearance, giving the impression, from a distance, of a wall of continuous glass (Figure 2.3b). The thin joints between frames seem to disappear at a distance [9].
Figure 2.2 - Example of capped system and SSG system: Forster Vario [19], Schüco UCC [20]

Figure 2.3 - Visual difference on exterior façade between capped system a) [21] and structural silicone system b) [22]
Possible improvement of the details

In order to improve the thermal performance of curtain wall design options, the following aspects should be analysed:

- Enhancing the properties of the materials employed for the different components such as frames, adhesives, sealant and spacers;
- Geometry of frames: the introduction of cavities in the frame or the percentage of matt surface can sensibly change the performance of the whole façade [7];
- Novel designs options: including the frame in the Insulated Glazing Unit or sealing the frame with the glazing internally can lead to reduce the thermal bridge effect.

Following some studies concerning the improvement of window thermal performance are presented, anyway their results can be applied to curtain wall systems as well.

Gustavsen et al. [23] analysed the effects of different surface emissivity frame material and spacer conductivities on frame and edge-of-glass U-factors. The goal of the work was to define material research targets for frame components that would result in better frame thermal performance, and to exhibit the best products available on the market today. The results showed that U-value decrease as spacer conductivity decreases. Changing the effective spacer conductivity from 10 to 0.25W/(mK), where 0.25W/(mK) is close to the effective conductivity for the best available spacers today, results in a decrease in frame U-factor of more than 18% for the frames studied in the paper.

Based on the literature survey and review of current commercial edge seal systems, Van Der Bergh et al. [24] identified research opportunities for future edge seal improvements and solutions. The spacer intended as an edge seal between glass panes, consists of different components:

- Spacer bar: traditionally in metal, the main function of the spacer bar is to hold the glass panes at a fixed distance from each other;
- Desiccant: used in insulating glazing units (IG) to prevent the inside glass surfaces from fogging because of condensation of moisture vapour or organic vapours. Moisture vapour might be trapped in the inter-pane space during manufacturing of the IG unit or can permeate through the edge seal while the IG unit is in use;
- Sealant: The sealant used in an edge seal structurally bonds the glass panes and spacer bar together while providing a high level of moisture vapour and gas diffusion resistance, allowing flexibility to accommodate glass movement.

These components are often combined and may serve more than one purpose (such as structural functionality and thermal performance). Numerical investigations show that total window U-value is
reduced by 6% when a traditional aluminium spacer is replaced with an insulating spacer in a standard double-glazed window that does not have low-emissivity (low-e) coating on any of the glass panes. The simulations analysed in the paper demonstrated that edge seals have a significant effect on the U-value of a glazing unit. Improvement in edge seal thermal performance can be achieved by reducing the heat transfer width of the edge seal, reducing its thermal conductivity, and increasing its thickness. Decreasing the width of spacer bar and secondary sealant reduces the size of the thermal bridge at the edge of glass, thus increasing thermal performance.

The study of new frame material was addressed in different research projects, for example stainless steel replacing aluminium can improve the frame U-value being a less conductive material, moreover the coefficient of thermal expansion of stainless steel (unlike the aluminium) is close to the glass one. As other possible solutions for frame material, Appelfeld et al. [25] presented the development of an energy efficient window frame made of a glass fibre reinforced polyester (GFRP) material. The potential benefit of GFRP window frames is in saving energy by lowering U-value of a window and increasing solar gains by reducing frame width.

Thanks to the developing technology, the performance of aluminium frames is nowadays comparable to the one of the wooden frames. The numerous air cavities inside aluminium frames suggest a deep investigation of the heat exchange process; Asdrubali et al. [7], analysed the effect of the geometric and surface characteristics of the cavities on the overall performance of the profile. The attention was focused on the emissivity properties of the cavity inner surfaces, since they play a fundamental role on radiation heat transfer. It was noted that the emissivity of a gap inner surfaces is highly influential on its thermal performance: the equivalent conductivity is reduced by 35% when the emissivity of an air gap surfaces varies from 0.90 to 0.06. Furthermore, the results show that the integration of an adequate number of gaskets, which has the effect of reducing the cavities dimensions and connections, reduces the thermal transmittance of the overall panel of about 10%.
3. NOVEL CURTAIN WALL CONNECTIONS: S+G PROJECT CASE STUDY

3.1 Description of the project

The basic idea of the S+G project is to define the conceptual design of an innovative system for unitized composite transparent envelopes to meet architectural, energetic and structural requirements. The new system would address the needs of standardised flat surfaces, but it could conveniently apply to free-form curved surfaces through the composition of steel with cold-formed-glass. To this extent different possibilities are given by:

- enhanced sealant properties (low thermal conductivity to meet energetic requirements, and reliable bonding between steel and glass to allow new geometrical shapes keeping the structural requirements);
- use of material with lower thermal conductivity and with similar thermal expansion of glass (stainless steel is used instead of aluminium);
- new geometries for mullion/transom elements given by the enhanced properties of the adhesive.

In this project, the choice of steel instead of aluminium, aims to build a cell which can be cold formed obtaining a curved shape. The choice of steel is related to its coefficient of thermal expansion which is of the same magnitude order of glass, indeed the coefficient of thermal expansion of glass ($\alpha \approx 9 \times 10^{-6} \, ^\circ\text{C}^{-1}$) is not compatible with that of aluminium ($\alpha \approx 24 \times 10^{-6} \, ^\circ\text{C}^{-1}$) but it is close to that of steel ($\alpha \approx 12 \times 10^{-6} \, ^\circ\text{C}^{-1}$) [26].

The general aim of the research project consists in the design and optimization of an innovative system for composite steel + glass units, to be used in buildings for both roofs and facades applications, able to join architectural, energetic and structural requirements enhancing the design possibility for new geometrical shapes.

Among the main tasks of the project there are:

- Improve in-service energy efficiency, by exploitation the low thermal conductivity of steel, especially with respect to aluminium (so far the predominant metal used in glazing applications) through: the experimental characterization of thermal properties of the full system in cold/hot box apparatus; the optimization of connections (insulating effect of the adhesive layers); the accurate simulation of building energy performance.
- Development of an innovative steel-framed unitized cell for standardized construction at competitive costs for a wide variety of glazing applications, including free-form surface
through cold-bending of glass, by optimizing: steel frame design; process to bond steel to glass by means of adhesives; methods for cold bending of glass; assembly and installation; aesthetic appearance; scrap material and waste; reuse and recycling.

3.2 Curtain wall design options

Three design options were developed in order to fulfil the objective of the project (Figure 3.1):

- **WING (WINged Glass):** it is a steel+adhesive+glass cell laminated in autoclave. The steel edges (wings) may be folded to occupy less space in autoclave and this minimizes also the costs of transportation. This idea was proposed to study the problem of creating a barrel vault structure by assembling different cells (through a *reciprocal beams* assembly). It is characterised by a self-supporting structure and by a pleasant design due to the reduce width of the frame (only 30mm);

- **HYP&R (HYPerbolic Paraboloid & Rotules):** The metal is reduced at minimum, since it is only present as plates on the edges of the glass panel. Due to the presence of the rotules it is not the most economical option, but a possible optimization of this solution in terms of costs can be the reduction of the number of rotules. It needs a load bearing structure to work. Two different HYP&R options were developed: in the first one a 45mm width frame and 1÷3mm thick adhesive (DC993 or TSSA) are used (*Figure 3.1 a*), the second one is characterised by a larger frame (85mm) and a different adhesive is used, SikaMove, which is 6mm thick (*Figure 3.1 b*));

- **TWIST (TWIsted STructure):** it is an elaborate solution, self-supporting also in the warping phase. Compared to the other solutions the TWIST is characterised by a tubular section which gives a more massive design. In order to realize this solution, a possibility is to first warp the frame and then force the glass panel on it putting at the end all the system in autoclave. The composite structure maintains a certain curvature and there is no spring back because of the adhesive.
Material Properties:

Adhesive:
A selection of most suitable adhesives to bond steel and glass was performed in the project. Among all products available on the market, three different materials were considered:

1) high performance structural silicone (DC993 [27], thermal conductivity $\lambda = 0.34$ W/mK);
2) polyurethane-based adhesives (SikaMove [28], thermal conductivity $\lambda = 0.29$ W/mK);
3) innovative Transparent Silicone Structural Adhesive (TSSA [29], thermal conductivity $\lambda = 0.20$ W/mK).

Mullion/Transom:
Stainless steel was chosen rather than aluminium to meet the project requirements, in terms of:

- formability, to fit the required frame element shapes;
- mechanical properties, to meet the design loads for the structure with reasonable deformation;
- durability, with respect to the corrosion caused by aggressive environments;
- thermal expansion, in order to minimize stresses in the adhesive layer and in the glass;
- thermal conductivity, sensibly lower compared to aluminium (22.5 W/mK against 160 W/mK).
Double glazing unit:

Double glazed insulating units were preferred because they represent, by far, the most popular glazing to meet the energy efficiency requirements. The project specifications suggested a 6-12-6 glazing unit with air filled gap, adopting a low emission layer ($\varepsilon=0.05$), with transmittance value $\approx 1.6 \text{ W/m}^2\text{K}$.

As no specifications were given regarding the spacer to employ in the DGU, different solutions will be analysed in the work currently conducted for the assessment of curtain wall thermal performance.

It was found that improving the spacer thermal performance can significantly reduce the negative influence of the edge seal on the overall window $U$-value [24]. This asserting will be tested in the following work by enhancing the performances of the spacer elements: spacer bar, desiccant, primary sealant and secondary sealant. Indeed, the spacer bar, traditionally in aluminium (high conductivity) can be replaced by a less conductive material (steel) or abolished by using a thermoplastic spacer (see section 6.2). At the same time, an accurate choice of the material employed as primary and secondary sealant can lead to the enhancement of the overall thermal performance.

<table>
<thead>
<tr>
<th>Mullion/Transom</th>
<th>Stainless steel</th>
<th>$\lambda = 22.5 \text{ W/mK}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive</td>
<td>Aluminium</td>
<td>$\lambda = 160 \text{ W/mK}$</td>
</tr>
<tr>
<td></td>
<td>DC993</td>
<td>$\lambda = 0.34 \text{ W/mK}$</td>
</tr>
<tr>
<td></td>
<td>SikaMove</td>
<td>$\lambda = 0.29 \text{ W/mK}$</td>
</tr>
<tr>
<td></td>
<td>TSSA</td>
<td>$\lambda = 0.20 \text{ W/mK}$</td>
</tr>
<tr>
<td>Glazing</td>
<td>DGU</td>
<td>$U_{\text{cop}} = 1.6 \text{ W/m}^2\text{K}$</td>
</tr>
</tbody>
</table>

Table 3.1 – Material properties: thermal conductivity and transmittance of the DGU
3.3 Methods: Numerical analysis and experimental analysis

Two methods were deployed in this work in order to develop high performance curtain wall connections and to test their level of performance compared with the state of the art ones: a numerical method and an experimental method. FEM analysis was performed with the software THERM, aiming at analysing the profile of temperatures (to assess the condensation risk) and the U-values of the details [30]. The purpose of the experimental analysis was the verification of the effective improvement of the performance in the new studied details and the comparison with the simulations.

3.3.1 Numerical assessment

The Finite-element method (FEM) program THERM was used to solve the conductive heat-transfer equation [8]. THERM’s quadrilateral mesh is automatically generated. The FEM program uses correlations to model convective heat transfer in air cavities and it can calculate radiation heat transfer using view factors or fixed radiation coefficients.

The performance analysed by means of the numerical assessment were:

- Thermal energy efficiency: by means of the linear heat transfer coefficient (Ψ-value [W/mK]) of the connection and overall U-value [W/m²K] of the whole CW system;
- Surface condensation risk: quantifiable with the lowest surface temperature measured on the indoor environment side of the connection;
- Structural integrity and durability: quantifiable by means of the highest temperature achieved by the different materials in the connection. This could also be used as boundary condition for structural verifications of differential thermal expansion.

The FEM analysis (chapter 4) was carried out on two stages:

1) A first simplified stage in order to understand the main factors influencing the performance of the curtain wall connections;
2) A second detailed stage to quantify the performance of the different design options and to propose modifications to the designs in order to improve their performance.

Four different S+G design options were analysed in the first stage (Figure 3.1). Seven different curtain wall connection design options were analysed in the second one: three for HYP&R, two for TWIST and two for WING design. The analysis of the different S+G design options were compared against a reference, representing the state-of-the-art of structural CW unitized systems connections. To this end the Schüco UCC SG was selected to be compared with the four S+G connections.
Connected to the FEM analysis, some optimisation of materials selection will be presented in the following chapters.

3.3.2 Experimental assessment

The experimental characterisation of the thermal energy performance of the S+G design options was performed by means of thermometric measurements in a climatic cell, located in Turin (BET cell). The climatic chamber is an apparatus in which a steady-state thermal flow is applied across the façade mock-up, this is achieved by controlling the temperature of the air in a hot and a cold chamber on either side of the mock-up. The rooms on either sides of the mock-up are controlled at two different temperatures usually simulating outdoor and indoor condition. Temperature and relative humidity can be controlled to follow the design conditions in both the cold box and in the hot box [3].

The evaluation of the thermal performance of the specimens was done by qualitatively and quantitatively characterizing the thermal bridge effect and its area of influence [31]. To quantify the $\Psi$-value two methods were adopted: a heat flux meter method (HFM) [32] and a thermographic method by means of an infrared camera (IR) [33].

For many years, hot box facilities have been used for thermal testing of inhomogeneous components, even if they have been applied with different standards throughout the world. At the Department of Industrial Engineering of the University of Perugia, a hot box apparatus was designed, built, and calibrated according to three different standards: the European EN ISO 8990, the American ASTM C1363-05 and the Russian GOST 26602.1-99. Using information from a literature review, the three approaches were compared, focusing on the differences of calibration and measurement procedures, and evaluating the uncertainties of each method. The three approaches were compared by the thermal transmittance evaluation of an aluminium framed window. The values obtained were very close, with a maximum difference of 3% [34].

The dynamic aspects of building envelope behaviour are receiving increasing amounts of attentions. Ferrari et al. for example performed an experimental analysis with a climatic chamber to compare the actual behaviour of envelope elements that were characterised by equivalent steady-state performances but different thermal inertia under actual service conditions [35]. There is a great uncertainty about the dynamic behaviour of thermal bridges. In Martin et al. a series of test were carried out in a guarded hot box testing facility in order to obtain more information about the thermal response of thermal bridge. In this case one of the main objectives of the study was the determination of the area of influence of the thermal bridge and the results were compared with the simulations [31].
3.3.3 Comparison between experiments and simulations

The results obtained by means of numerical assessment and experimental assessment, were consequently compared to validate the simulation model. The aim of the validation is to obtain a simulation model that can represent results as close as possible to the reality. Once the model is considered validated, the thermal performance of the different systems can be tested under several boundary conditions and the desired modifications can be deployed in order to evaluate the effective improvements on the overall performance.

The validation of the model consists in the comparison between the results obtained with the FEM analysis and those measured by means of the experimental analysis. To this purpose the same boundary conditions measured in the climatic cell were applied to the simulation model.
4. NUMERICAL ASSESSMENT: FEM ANALYSIS

The performance of the S+G connection is defined in terms of:

- Thermal energy efficiency: quantifiable in terms of the linear heat transfer coefficient (Ψ-value [W/mK]) of the connection and in terms of surface overall specific heat transfer coefficient (U-value [W/m²K]) of the whole unitized system adopting a specific connection;

- Surface condensation risk: quantifiable with the lowest surface temperature measured on the indoor environment side of the connection, which should be lower than the dew point temperature for specific boundary conditions;

- Structural integrity and durability: quantifiable by means of the highest temperature achieved by the different materials in the connection in worst case scenario boundary conditions, i.e. high outdoor temperature and with high perpendicular solar radiation.

The analysis of the connections was performed with the software THERM 7.2 (developed by LBNL of US Department of Energy) where the two-dimensional conduction heat-transfer analysis is based on a finite-element method [8]. FEM is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variation methods from the calculus of variations to solve the problem by minimizing an associated error function [36]. THERM is one of the most used FEM thermal models free of use. While the model for the insulated glazing was done with the software WINDOW (also developed by LBNL).

In the FEM analysis EN ISO boundary conditions were applied [37]:

- External conditions: Temperature = 0°C, Film coefficient = 23 W/m²K;
- Internal conditions: Temperature = 20°C, Film coefficient for glass = 8.02 W/m²K, Film coefficient for frame = 7.71 W/m²K;
- Relative Humidity : 50%;
- Edge of the glass length (distance from frame in order to have undisturbed one dimensional heat flow) : 190 mm;

The analysis of the different S+G design options were compared against a reference, representing the state-of-the-art of structural CW unitized systems connections. To this end the Schüco UCC SG was selected to be compared with the four S+G connections.
4.1 Detailed S+G design options

The different designs studied are showed in Figure 4.1. The two HYP&R design differ for the adhesive used (SikaMove or TSSA) and the dimension of the frame plate. TSSA adhesive was employed in both TWIST and WING. Stainless steel 470 LI was for the frame components. As the Schüco UCC is originally in aluminium frame, an additional version using stainless steel was simulated in order to have a fairer term of comparison.

A 6-12-6 double glazing unit (DGU) with air filled gap and low-e film on face 3 ($\varepsilon = 0.05$) was used to be connected with the S+G frames, the calculated U-value for the DGU is 1.63 W/m$^2$K. The material properties in THERM were set according to available project specification at the initial stage: double sealed aluminium spacer (butyl rubber as primary sealant and polysulphide as secondary sealant); emissivity of the stainless steel 0.8 (no accurate data were available at that stage); thermal conductivity of materials according to the characterization performed. The material physical properties used are summarized in Table 4.1.

### Table 4.1 - Detailed design material properties

<table>
<thead>
<tr>
<th>Frame</th>
<th>Stainless Steel</th>
<th>$\lambda = 22.5 \text{ W/mK}$</th>
<th>$\varepsilon = 0.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminium</td>
<td>$\lambda = 160 \text{ W/mK}$</td>
<td>$\varepsilon = 0.8$</td>
</tr>
<tr>
<td>Adhesive</td>
<td>TSSA</td>
<td>$\lambda = 0.20 \text{ W/mK}$</td>
<td>$t = 1 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>SikaMove</td>
<td>$\lambda = 0.29 \text{ W/mK}$</td>
<td>$t = 6 \text{ mm}$</td>
</tr>
<tr>
<td>Spacer</td>
<td>Silica Gel</td>
<td>$\lambda = 0.03 \text{ W/mK}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminium alloys</td>
<td>$\lambda = 160 \text{ W/mK}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Butyl rubber (primary sealant)</td>
<td>$\lambda = 0.24 \text{ W/mK}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polysulphide (secondary sealant)</td>
<td>$\lambda = 0.4 \text{ W/mK}$</td>
<td></td>
</tr>
</tbody>
</table>
4.2 U-values

The U-values resulting from the simulations are illustrated in Figure 4.2. In the graph the U-value corresponding to the frame, the edge (area between the frame and the centre of panel), centre of panel and total unitized system are showed. For the calculation of the total U-value of the unitized system a 1.5m x 3.5m unitized façade was considered. As far as the HYP&R designs are concerned, the frame U-value used for the total panel transmittance is a weighted value that takes into consideration the surface influenced by the rotules as shown in Figure 4.3. It is possible to observe that the high U-values of frames are not compromising the total transmittance; this is due to the limited frame surface compared to the glass one.

As far as the U-frame values are concerned, all the four design options except the WING one, perform better than the Schueco design options (aluminium and stainless steel). This is mainly due to the fact that there is no direct connection between indoor and outdoor environment through lower insulating
materials in the connections, as the frame is completely attached to the inner surface of the glazing. As far as the overall U-values are concerned, all the design options, including the WING frame, perform better than the Schueco reference connection. The reason stands in the discrete frame design (and consequently small amount of conductive metal) for all the S+G frame options. All the four designs have reached at least the same level of performance of the Schüco UCC SG. The best performing design concerning U-values are the two HYP&R and the TWIST. This is due to the fact that the frame and the low conductive adhesive extend beyond the area corresponding to the spacer of the glazing, improving the U-value of the edge area beyond the one of the centre of panel, as they provide additional back insulation to the glazing unit. Although improving the thermal energy efficiency performance, this could be detrimental in terms of structural integrity and durability of the connection and of the glazing. In fact high temperatures can be achieved in the materials in the connection and the glazing (primary sealant especially).

The TWIST design option seems to have the lowest U-value, although it should be stated that the software used adopts a simplified radiative and convective heat transfer model for the closed cavity of the frame. This model is expected to underestimate the actual heat exchange in the TWIST frame close cavity, resulting in lower U-values of the frame calculated.

4.3 Condensation risk assessment

For the evaluation of the condensation risk, the dew point temperature corresponding to 20°C and relative humidity of 65%, that is 13.2°C [38]. The condensation will occur as the indoor surface temperature of the connection or the glazing drops equal or below the dew point temperature. In Figure 4.4 and Figure 4.5 the colourful isotherms for the design options are shown and the lowest surface temperature found per each detail is indicated in the temperature legend. The lowest temperature is always observed close to the connection between two different panels, where the frame and adhesive meet the glass. On the contrary in the Schüco design as the connection between two panels is protected by the frame itself, thus the lowest temperature occurs in the structural silicon dealing the frame to the glass. Therefore, even if the HYP&R SikaMove and the TWIST design where the best performing as far as the total U-values are concerned, the lowest temperatures are below the dew point, hence condensation occurs.

Therefore some options have to be further explored and improvement proposed in order to avoid condensation. The improved design options could consist in: adopting a warm-edge spacer in the glazing unit; increasing the emissivity of the metal used; protecting the points in which the lowest temperature is likely to occur by means of increased thermal resistance (such as some silicon sealant applied on the internal side).
The poorest performing design options as far as condensation risk is concerned are the TWIST and HYP&R SikaMove connections. While WING and HYP&R TSSA presents no condensation risk.

![Infrared colour illustration of Schüco design with indication on the minimum surface temperature](image1)

![Infrared colour illustration of studied designs with indication on the minimum surface temperature](image2)
4.4 Improvement of first detailed design options

After the S+G meeting held in Cambridge on September 2014 some design input data were changed and the analysis updated, according to the new project specifications, the newer available material characterizations and the improved design options, as suggested by the analysis on the first detailed design options. The main design variations were:

- adoption of surface finish with the lowest stainless steel emissivity available (0.26) according to the manufacturer measurements and recommendation;
- adoption of warm-edge spacer for the glazing: stainless steel spacer with polyisobutylene primary sealant and silicon secondary sealant [39];
- Evaluation of additional design options, employing DC 993 instead of TSSA adhesive (a thickness of 3 mm was adopted for DC993 designs).

The analysis were updated by varying one parameter at the time, in order to effectively register performance improvements, if any, compared to the first design option presented in Section 3, due to a specific change in design.

Five different design alternatives for each S+G design options resulted from these modifications:

1. Original design with steel emissivity of 0.8 and spacer with average performance;
2. Design with steel emissivity of 0.26 and average spacer;
3. Design with steel emissivity of 0.8 and warm edge spacer;
4. Design in which both low steel emissivity and warm edge spacer are adopted;
5. Design using aluminium (\(\lambda = 160 \text{ W/mK}, \varepsilon=0.8\)) and warm edge spacer to evaluate the actual improvement deriving by using stainless steel instead of a more conductive metal.

The S+G design options become 7 (from the original number of 4), given the additional design options adopting the DC993.

4.5 Analysis of improved detailed design options

In this section the results for the different 7 different design options (5 design alternatives each) and the Schueco reference connections are presented. Each steel design in the last configuration was also compared to the same detail using aluminium an frame (\(\varepsilon=0.8\) and \(\lambda=160 \text{ W/mK}\)) to evaluate the magnitude of the improvements, if any, obtained by using stainless steel instead of aluminium in the frame.
4.5.1 Total transmittance values and frame transmittance values

The total transmittance values considering a 1.5 m x 3.5 m are represented in Figure 4.6 and Figure 4.7. For all the design options the employment of a warm-edge spacer improved significantly the U-value, more than decreasing the steel emissivity. An exception is represented by the HYP&R designs, in which the effect of decreasing the thermal conductivity of the spacer on the overall U-value is of the same magnitude of the effect of varying the emissivity of the metal. The comparison within the same design option, with the aluminium frame shows the enhancement of the transmittance using the stainless steel frame. While the comparison between the Schueco steel reference configuration, or between the aluminium S+G and the aluminium Schueco reference, shows the improvements achieved by the different design (due to a change in geometry and use of innovative adhesive connection).

Figure 4.8 and Figure 4.9 represent the performance of the frame in terms of U-values for the different design options and configurations. Here is possible to better appreciate the improvement that has been achieved using the warm edge spacer, this is more significant compared to that one obtained decreasing the emissivity of the steel, which is nevertheless concurrent in lowering U-values. The considerable improvements of the frame U-values are not always translated in sensibly better total U-values; this is due to the small portion of frame surface compared to the glass one in the façade panel. The most effective parameters in terms of U-value, of both frame and whole unitized system, in decreasing importance ranking are:

1. geometry;
2. conductivity of metal used for the frame;
3. spacer;
4. emissivity of the metal surface exposed to the indoor environment.

As far as the HYP&R design options are concerned, in Figure 4.10 the variability of the frame U-value considering the section with and without the rotule is presented. As the rotules are point components the total value of the frame transmittance was calculated considering the frame area influenced by the rotule itself. This area and the corresponding U-value takes into account the decreasing effect of the rotule at increasing distance.

Considering the total U-value, The HYP&R and TWIST design options perform better compared to the WING and to the reference Schüco UCC. According to these analysis decreasing the spacer thermal conductivity and the metal emissivity can lead to a 6-7% reduction of the overall U-values compared to the Schueco UCC design, and to 4-5% compared to S+G first design options (0.8 emissivity of metal and conventional spacer), considering a unitized façade with 1.5 m x 3.5 m frontal sizes.
Figure 4.6 - Variability of total U-values over variability of spacer λ and steel ε

Figure 4.7 - Variability of total U-values over variability of spacer λ and steel ε
Figure 4.8 - Variability of Frame U-values over variability of spacer $\lambda$ and steel $\varepsilon$

Figure 4.9 - Variability of Frame U-values over variability of spacer $\lambda$ and steel $\varepsilon$
4.5.2 Condensation risk assessment

As shown for the transmittance values Figure 4.11 and Figure 4.12 show the variability of the lowest indoor surface temperature in each design option due to the different design alternatives. The surface temperature should be higher than the dew point temperature to avoid condensation, that for indoor air temperature at 20°C and relative humidity of 65% is equal to 13.2°C [38].
From the results it is possible to see that using a better performing spacer results in an increased lowest temperature, while the use of 0.26 emissivity steel instead of the 0.8 decreases the temperature of 0.2°C in almost every design option. While the design alternatives using aluminium present lower U-values, they have higher surface temperatures as far as the critical points for condensation are concerned. This can be explained because the radiative flux exchanged between the surface close to the frame and the metal is higher for higher metal emissivity and this increases the temperatures close to the frame surface, as the indoor radiant temperature is higher than the surface one.

The TWIST design seems to be the weakest as far as the condensation risk is concerned, indeed the temperatures are very close to 13.2°C. In the case of TWIST with TSSA adhesive a higher emissivity has to be preferred in order to increase the temperature of the critical points and to avoid condensation. The HYP&R with SikaMove adhesive presents temperatures lower than the dew point in the original design, but they increased with the employment of a better performing spacer. All the other details show temperatures that are not critical as far as the condensation risk is concerned.

4.5.3 Linear thermal transmittance $\Psi$

The aim of the heat flow meter analysis is the evaluation of the thermal performance of the S+G design options by quantifying the linear transmittance value. The linear transmittance value $\Psi$
[W/mK] was calculated according to the EN/ISO 10211-1 [40]. Ψ is the additional heat flow across the mock-ups by meter length and one degree temperature difference due to the thermal bridge, compared to the one dimensional heat flow, both in steady state conditions:

$$ Q_{2D} = U_{1D} \cdot A_{Tot} \cdot \Delta T + \Psi \cdot l \cdot \Delta T \quad [W] $$  \hspace{0.5cm} (4.1) 

Where:

Ψ is the linear thermal transmittance of the linear thermal bridge separating the two environments being considered [W/mK];

$A_{tot}$ is the total area of the component [m$^2$];

$U_{1D}$ is the thermal transmittance of the 1-D component $k$ separating the two environments being considered [W/m$^2$K];

$l$ is the length of the component characterised by the thermal bridge [m];

$\Delta T$ is air temperature difference between the two environments [K].

$Q_{2D}$ [W] is given by the transmittance value of the frame, edge of glass and centre of panel multiplied for the corresponding area of influence and $\Delta T$. The thermal bridge length $l$ is 10 meters (perimeter of the panel 1.5x3.5m). While the 1-D component is the one to which the conditions of the centre of panel are applied (Figure 4.13).
The $\Psi$-value was then calculated from the results from THERM as follows:

$$Q_{2D} = (U_{frame} \cdot A_{frame} + U_{edge} \cdot A_{edge} + U_{COP} \cdot A_{COP}) \cdot \Delta T \quad [W]$$  \hspace{1cm} (4.2)

$$Q_{1D} = U_{COP} \cdot A_{Tot} \cdot \Delta T \quad [W]$$  \hspace{1cm} (4.3)

$$\Psi = \frac{Q_{2D} - Q_{1D}}{\Delta T_l} \quad [W/mK]$$  \hspace{1cm} (4.4)

The best performing final design alternatives, among the 7 analysed in this second stage of analysis, for the S+G connections are the one adopting a warm edge spacer and steel emissivity of 0.26.
Therefore the $\Psi$-values [W/mK] of these final options are reported in Table 4.2. These values allow a direct comparison of the connection thermal performance per unit length. The best designs in terms of thermal energy efficiency, according to this analysis, are the HYP&R and TWIST design option (35% improvement compared to the reference), while 15% improvement is achieved with the WING design option. The adhesive used does not have a significant effect on the $\Psi$-values, due to the relatively low change in thermal resistance introduced in the connection. It has to be considered that in the case of the TWIST design option, a simplified model was used for the convective heat exchange in the closed frame cavity due to FEM software limitations. This could result in inaccurate (overestimated) performance estimation of TWIST design, but this could be assessed in future activity (numerically or experimentally).

### Table 4.2 - Calculated thermal linear transmittance for the different designs

<table>
<thead>
<tr>
<th></th>
<th>SCHU CO Al</th>
<th>SCHU CO Steel</th>
<th>HYP&amp;R Sika</th>
<th>HYP&amp;R TSSA</th>
<th>HYP&amp;R DC</th>
<th>TWIST TSSA</th>
<th>TWIST DC</th>
<th>WING TSSA</th>
<th>WING DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi$ values</td>
<td>0.178</td>
<td>0.154</td>
<td>0.118</td>
<td>0.116</td>
<td>0.116</td>
<td>0.112</td>
<td>0.115</td>
<td>0.154</td>
<td>0.151</td>
</tr>
</tbody>
</table>

4.6 Final considerations

In this section a general rule of thumb for design purposes is presented regarding the influence of the variation of certain material properties on the connection thermal performance. The variation of spacer conductivity and steel emissivity has changed the thermal performance of the designs studied as far as U-values and minimum surface temperatures were concerned. Below (Figure 4.14) it is outlined how the single parameters have changed the performance of the design. Decreasing the spacer conductivity has the effect of increasing the lowest temperatures and decreasing U-values. Decreasing the adhesive conductivity has the effect of increasing the lowest surface temperatures while the U-values remained almost unchanged. Regarding the frame, improving the material properties has the effect of decreasing the U-values and the lowest surface temperatures. It is possible to suppose that as the frame component is decoupled from the panel (glazing) through the adhesive (the red dashed line in Figure 4.14), the variation of its physical properties does not affect in a sensible way the overall thermal performance. The influence of the frame material would have been higher in case of structural connections inside the glazing unit.
The TWIST design has been found to be the weakest as far as the surface temperature is concerned. Possible improvement can be achieved with small modification to the design to reduce the uncovered surface area between two panels. It was simulated that a simple addiction of a layer of silicone (operation that can easily be done during the installation) can sensibly increase the temperature values of the critical points from 13.2°C to 14.7°C avoiding condensation (Figure 4.15).

On the overall it was found that the best performing design option for each performance parameter is different, and that a trade-off is always needed. In fact the best performing design in terms of U-value are all the HYP&R design options, while the experimental analysis is needed to confirm the results for the TWIST. The WING design although achieving not a very good performance in terms of U-value, outperforms the other solutions in terms of condensation risk and high temperature achievable in the materials of the connection, moreover it presents a high added aesthetical value due to the relatively thin frame.
5. EXPERIMENTAL ASSESSMENT BY MEANS OF CLIMATIC CELL

The topic of this section is the experimental characterisation of the thermal energy performance of the S+G design options by means of thermometric measurements in a climatic cell, located in Turin (BET cell). The use of the cell was kindly offered by TEBE research group, headed by Prof. Marco Perino. The main purpose of these measurements is the experimental characterization of the thermal performance of the S+G design options and the validation of the FEM model. A thermometric analysis was carried out instead of a calorimetric one (according to EN ISO 12567 and 12412) for the following reasons:

- to experimentally characterize as many design options as possible within the budget;
- to control the experimental environment in order to have enough data to validate the FEM model (boundary conditions of the test are needed i.e. air and surface temperature, surface heat exchange coefficients, etc…).

However a further calorimetric analysis by means of a hot box apparatus owned by the EMPA in Zurich will be performed for one of the four S+G design options.

The evaluation of the thermal performance of the specimens was done by qualitatively and quantitatively characterizing the thermal bridge effect and its area of influence [31]. To this end the linear thermal transmittance ($\Psi$-value [W/mK]) was calculated. It can be defined as the additional heat flux due to the thermal bridge, compared to the undisturbed one dimensional heat flow measured on the same surface, per meter length of the thermal bridge and for a temperature difference of 1°C [40]. To quantify the $\Psi$-value two methods were adopted: a heat flux meter method (HFM) [32] and a thermographic method by means of an infrared camera (IR) [33].

5.1 Experimental set-up

The climatic chamber is an apparatus in which a steady-state thermal flow is applied across the façade mock-up, this is achieved by controlling the temperature of the air in a hot and a cold chamber on either side of the mock-up (Figure 5.1). The overall sizes of the climatic chamber used are 2.74 m width, 4.84 m length and 2.34 m height. The innovative nature of the Building Envelope Test cell allows, among the others, the regulation of wall thickness in order to fit every kind of façade design with frontal dimension smaller than 2.34 x 2.74 m, and with thickness smaller than 0.5m. The rooms on either sides of the mock-up are controlled at two different temperatures usually simulating outdoor
and indoor condition. Temperature and relative humidity can be controlled to follow the design conditions in both the cold box and in the hot box [3].

The typical specimen tested in this experiment was a glass façade composed of the four different S+G options (Figure 5.2): HYP&R Sika, HYP&R DC993, TWIST and WING (the adhesive DC993 replaced the TSSA, as delamination of TSSA adhesive from the stainless steel frame on the linear connection was experienced during mock-up preparation). An opaque panel made of MDF + XPS (thickness of 0.027m and thermal conductivity of 0.04 W/mK) was used as thermal insulation on the top and on the side of the glass façade.

Details of the four design options are shown in Figure 5.3. Plan view and sections of the climatic cell are shown from Figure 5.4 to Figure 5.6. In the drawings the sensors set up and names are indicated. The four mock-ups (1m x 1m) have been provided by TRIMO and installed as shown in Figure 5.7 (the numbers 1, 2 and 3 refer to the position where the picture was taken, explained in the plan view in Figure 5.4). A curtain was installed both in the cold and in the hot chamber, respectively at 1.30 m and 1.00 m from the façade. The curtain was placed in order to ensure spatial and temporal uniformity of air temperature and a lower variation of convective heat exchange, which was due to the cooling and heating systems.
Figure 5.2 - Configuration of the cell, showing the glass façade and the curtain installed

Figure 5.3 - Detail of the S+G design options

1. Polysobutylene (PIB) \( \lambda = 0.2 \text{ W/mK} 
2. Aluminium layer \( \lambda = 160 \text{ W/mK} \ t = 0.4\text{mm} 
3. Silica Gel \( \lambda = 0.03 \text{ W/mK} 
4. Silicone \( \lambda = 0.2 \text{ W/mK} 
5. DC993 \( \lambda = 0.35 \text{ W/mK} 
6. Steel 470. L1 \( \lambda = 22.5 \text{ W/mK} \ \epsilon = 0.26 \)
ASSESSING THE THERMAL PERFORMANCE OF GLAZED CURTAIN WALL SYSTEMS

EXPERIMENTAL ASSESSMENT BY MEANS OF CLIMATIC CELL

Figure 5.4 - Plan view of the climatic cell and placement of the thermocouples.

Figure 5.5 - Section B-B’ of the climatic cell and placement of the thermocouples
Figure 5.6 - Section C-C’ of the climatic cell and placement of the thermocouples

Figure 5.7 - Installation of the mock-ups: a) WING, b) HYP&R DC993, c) HYP&R SikaMove, d) TWIST

Regulation of temperature

All the measurements were performed under steady state conditions with a 25-28°C stable temperature difference between hot and cold side of the mock-ups. The cold chamber is cooled by an air conditioning unit controlled from the outside, with a cooling set point temperature of 12°C and relative
humidity of 35%. The hot chamber is heated by a radiator equipped with a PID controller, with a heating set point of 40°C. A fan has been placed facing the radiator in order to avoid air stratification and instability of surface heat transfer coefficients on the mock-ups surface.

**Equipment used**

Two different types of heat flux meter were used: the HFP01-10 produced by Hukseflux and the MF-180 produced by Eko (Figure 5.8). A total of 8 heat flux sensors were employed during the measurements: four Eko and four Hukseflux.

![Heat flow sensors used: a) HFP01 by Hukseflux, b) MF-180 by Eko](image)

HFP01 serves to measure the heat that flows through the object in which it is incorporated or on which it is mounted. The actual sensor in HFP01 is a thermopile. This thermopile measures the differential temperature across the ceramics-plastic composite body of HFP01. Working completely passive, HFP01 generates a small output voltage proportional to the local heat flux. The sensitivity is 50µV/W/m² and the dimension is 80mm as diameter. The MF-180 has a high sensitivity in spite of the small size. It is suitable for measuring a small heat flow generating a detectable output. The sensitivity at 20°C is 0.028mV/W/m² and its dimensions are 42 x 20 x 0.9mm.

Thirty thermocouples of type-T were employed during the measurements. TT thermocouples are sensors used to measure either the surface temperature of an object or the temperature of a fluid (i.e. air). They are composed by two clews, one in copper (positive pole) and one in constantan (negative pole), welded together.

Datataker dT85 was used for the acquisition of the temperatures detected by the thermocouples while the dT600 was connected to the eight heat flow sensors (Figure 5.9). The data logger is an electronic device that records data over time. The download of the physical data detected is possible connecting...
the logger to a computer. The two data loggers were synchronized and the data were recorded every 2 minutes.

![Datataker used for the measurements acquisition: a) dT85, b) dT600](image)

The IR camera used in these experimental tests is a TESTO 875-2i (Figure 5.10). The infrared radiation emitted from the object is detected and converted into electrical signal by means of an uncooled sensor, which consists of an array of sensitive elements disposed on a focal plane; the analogue temperature signal is amplified and converted into a digital signal displayed as a thermal image in colours or in black and white. The field of view of the camera (minimum distance of the focus) is 32°x23°/0.1m, the type of detector is a FPA 160x120 pixels, the spectrum of measurement is 8-14µm and the accuracy is ±2°C.

In order to avoid the "narcissus" phenomenon (reflection of the operator on the measured surface in the IR-spectrum) a black layer was placed on both sides of the glass and the sensors were applied on it.

![a) TESTO 875-2i thermal imaging camera, b) Set-up of the camera in the cell](image)
5.2 Calibration of measurements apparatus

The calibration of the measurements apparatus is needed in order to minimize the error due to the accuracies of the sensors used. The accuracies of the measurements apparatus are shown in Table 5.1: the values correspond to a Confidence Interval of 95% (CI: 95%).

<table>
<thead>
<tr>
<th>TT</th>
<th>T_IR</th>
<th>Heat flow</th>
<th>l_0 &amp; l_10</th>
<th>T_pr</th>
<th>T_refl</th>
<th>L</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>comparing T_IR and TT</td>
<td>spot measurement</td>
<td>known ε / spot measurements</td>
<td>known ε / avg measurements</td>
<td>Heat flow</td>
<td>l_0 &amp; l_10</td>
<td>T_pr</td>
<td>T_refl</td>
</tr>
<tr>
<td>Max [°C]</td>
<td>[°C]</td>
<td>[%]</td>
<td>[%]</td>
<td>[°C]</td>
<td>[°C]</td>
<td>[m]</td>
<td>[°C]</td>
</tr>
<tr>
<td>0,2</td>
<td>0,02</td>
<td>2</td>
<td>0,6</td>
<td>0,3</td>
<td>5</td>
<td>10</td>
<td>0,009</td>
</tr>
</tbody>
</table>

To calibrate the thermocouples within their operating range (-20°C to 80°C), their measurements were compared against the measurement of a reference platinum resistance thermometer PT-100 (which has a higher accuracy) at three different temperatures in water thermal bath (i.e. 0°C, 30°C and 60°C). The deviation of the measurements of each thermocouple form the PT-100 was expressed by the equation of a trend line \((y=mx+q)\). The coefficient \(m\) and \(q\) were used in the Datataker program to set the calibration of the thermocouples.

The air temperature was measured by three thermocouples in each environment (hot and cold). The sensors were placed at three different heights form the floor (50-100-150 cm), respectively in correspondence of middle height of the lower mock-up, of the connection between two mock-ups, and of the middle height of the upper mock-up. The average measurement was used as the air temperature value in the analysis. Only data measured in steady state conditions (stable air temperature in both environments) were considered for the subsequent analysis. Figure 5.11 shows the trend of the air measured in both environments. In the cold chamber (OUT) the air stratification is enhanced, moreover the temperature is influenced by the intermittence of the air conditioning unit, while in the hot (IN) chamber the temperature profile is more stable and homogeneous. The trend of the surface coefficients calculated on the cold and warm surface of the opaque panel and of the centre of glass \((Figure 5.12)\) shows the steadiness of the climatic cell conditions: for the opaque panel \(h_{out}\) is about 8.5 W/m^2K and \(h_{in}\) is about 5 W/m^2K, on the centre of panel of the glass mock-up \(h_{out}\) is around 8 W/m^2K and \(h_{in}\) is in the range of 10 W/m^2K.
Figure 5.11 - Trend of the air temperature detected at different heights, the red area shows the measurements discarded as representative of instable conditions of climatic cell.

Figure 5.12 - Trend of the surface heat transfer coefficient on the cold surface and on the warm surface of the panel and of the glass mock-up

In order to calibrate the heat flow sensors, a series of tests was performed on the opaque panel (MDF+XPS) before starting the measurements on the S+G designs. The eight heat flow sensors were placed on the same side of the panel while three thermocouples per side were used to detect the surface temperatures. The outcome of these measurements was the calculation of the conductance $C$ [W/m$^2$K] and the thermal conductivity $\lambda$ [W/mK] as $\lambda=C/t$, ($t$ is the thickness of the opaque panel).

Several tests were performed placing the heat flow sensors on the cold side or on the hot side of the panel. The thermal conductivities measured by each heat flow sensor, for each test, were compared with the $\lambda$ measured by means of a hot plate apparatus, because of the higher accuracy of the latter. The results of the hot plate apparatus tests on the opaque panel are presented in Figure 5.13.
ASSESSING THE THERMAL PERFORMANCE OF GLAZED CURTAIN WALL SYSTEMS

EXPERIMENTAL ASSESSMENT BY MEANS OF CLIMATIC CELL

Figure 5.13 - Hot plate measurements results: the test was performed for three mean temperatures to obtain a straight line both with upward heat flow and downward heat flow. The equation of the average straight line was used to calculate the equivalent $\lambda$ (depending on the mean temperature) that was compared to the thermal conductivities of the HFM tests.

The deviation of the $\lambda$ calculated for each sensor from the one measured by the hot plate is shown in Figure 5.14. Given that the accuracy of Hukseflux HFM is 5%, and that one of the Eko is 10% (C.I. 95%), as shown by the dashed red line in Figure 5.14, there was no need or any compensation of the heat flow measurements.

Figure 5.14 - Deviation of the $\lambda$ measured by means of each HFM from the $\lambda$ values measured with the hot plate.

Another source of inaccuracy is represented by the inability of covering the thermocouples with the same material of the surface measured (glass). Moreover a black tape is used on the glass in order to avoid “narcissus” effect. Due to the different emissivity of the tape used to stick the thermocouples on the surface (either aluminium or black tape Figure 5.15), a different temperature was sensed for the same surface. This is due to the different radiative heat exchange, proportional to the emissivity of the
tape ($\varepsilon \approx 0.05$ for the aluminium tape and $\varepsilon \approx 0.95$ for the black tape). In order not to affect the measurement the tape used should have an emissivity as close as possible to that one of the surface of interest. For this reason during the experiments on the S+G mock-ups, all the sensors on the glass were placed using the black tape, while the sensors on the stainless steel were attached with the aluminized tape.

![Different tapes used to place the sensors](image)

5.3 Experimental procedure

The sensors were placed as follows (Figure 5.16 is an example of the sensors set-up on the curtain wall surface, from Figure 5.4 to Figure 5.6 the set-up of the thermocouples in both environments is shown):

- 8 heat flow sensors: 7 heat flow sensors on the cold surface and one on the warm surface on the centre of panel;
- 14 thermocouples on the surface of the component: one thermocouple placed at the same height of the heat flux meters on the cold and on the warm surface;
- 6 thermocouples on air: three thermocouple per each room positioned at 50-100-150 cm from the floor in order to detect the average air temperature;
- 10 thermocouple on the environment surfaces: one thermocouple per each surface surrounding the façade in both chambers (floor, ceiling, curtain, wall on the left, wall on the right).

A complete list of the sensors is provided in Annex 1.
Figure 5.16 - Placement of sensors on the WING design seen from the cold side. The distance from the edge is on the y-axis. Each thermocouple on the cold side has corresponding thermocouple on the warm side at the same distance from the joint.

The Eko heat flow meters were placed on the thermal bridge in order to capture the profile of the heat flow density with higher resolution. According to the consideration deriving from the section 5.2 all the sensors have been placed using the black tape with the exception of the thermocouples on the steel frame which have been attached with the aluminate tape as the stainless steel emissivity (0.26) is closer to the one of the aluminium tape.

**IR experimental procedure**

The IR camera was positioned on the tripod, inside the thermostatic chamber in the cold environment. The height of the tripod varied depending on the position of the panel, whether up or down, to ensure that both the thermal bridge and the undisturbed area were included in the field of view of the IR camera. The IR camera logged every minute for each test lasting about half an hour. The mean planar radiant temperature $T_{ref}$ is measured with the IR camera by measuring the temperature of a reflective aluminium tape, and compared to the one calculated with the view factors of the cold chamber and with the measured surface temperature by means of the thermocouples. After determining the planar radiant temperature and the emissivity, the area, containing both the area disturbed by the thermal bridge and the undisturbed one, was identified on each thermal image, for each test, and then underlined in the corresponding array. This technique of processing thermograms was already experimented by Asdrubali et al [33]. The difference between the process used in the article mentioned...
and the one used in this experiment is that, instead of considering only one column of pixels, multiple columns were selected and averaged. In this way it was possible to obtain more precise measurements, having available a greater number of pixels and therefore of temperatures. In each thermal image ten columns were selected. In the sample images below (Figure 5.17) it is possible to see the selected area (red area).

Figure 5.17 - Placement the sensors of the aluminate tapes to indicate the scale of measurement (HYP&R Sika). The hatched red area indicates the area visualised during the thermography, while the red area indicates the ten selected columns to process the thermal bridge and the undisturbed area.

Figure 5.18 - Sample thermal image in which is shown the red area of the processed columns and the distance between a tape and the other.
Some small aluminate tapes (with much lower emissivity compared to the black tape in order to be easily detected in the thermal image) were fixed to the façade to determine the location of the selected temperature arrays and to identify the beginning of the area disturbed by the thermal bridge. These tapes, which basically were to indicate a measurement scale, have been positioned at precise distances (Figure 5.18). The dimension of a pixel was determined as follows: basing on the spatial resolution (FOV) of the lens used by the IR camera, it is possible to determine the size of the smallest identifiable object shown as one pixel. The IFOV parameter is proportional to the IR camera-to-object distance:

$$IFOV = FOV \times d$$  \hspace{1cm} (5.1)

The distance d was measured each time, before the beginning each measurement. Knowing the size of the pixel, the size of the areas of interest was calculated for each thermal image referring to each panel. In this way it was possible to relate the surface temperatures to the entire length $l_{TOT}$ (Figure 5.19). The area of influence of the thermal bridge is defined as the extension of the thermal bridge, multiplied by the $l_b$. The $l_b$ is defined along the line perpendicular to the thermal bridge and its length extends until a distance from the thermal bridge, corresponding to 99% of the total temperature difference along the line, is achieved. The $l_{ID}$, the entire undisturbed area, is calculated as the difference between $l_{TOT}$ and the length of $l_b$.

![Figure 5.19 - Example calculation $l_b$ on a thermal image of a panel](image)

For the calibration of the IR camera, an area is selected on the thermogram and the average temperature of the area is compared with the one measured by the thermocouple. For each thermogram an apparent emissivity was calculated in order to reach a temperature value as close as possible to that one of the thermocouple. Finally the average emissivity $\varepsilon$ calculated as in Figure 5.20 was set as the $\varepsilon$
value for the IR camera (it should be specified that the emissivity is apparent and not the real one of the material).

![Graph showing emissivity values for each thermogram and identification of the average value used for calculations.]

**Figure 5.20 - Emissivity values for each thermogram and identification of the average value used for calculations**

5.4 Thermal bridge characterisation methods

5.4.1 HFM analysis

The aim of the heat flow meter analysis is the evaluation of the thermal performance of the S+G design options by quantifying the linear transmittance value. The physical data measured are the heat fluxes passing through the components and the temperatures on both surface and in both environments (Figure 5.16).

The linear transmittance value $\Psi$ [W/mK] was calculated according to the EN/ISO 10211-1 [40]. $\Psi$ is the additional heat flow across the mock-ups by meter length and one degree temperature difference due to the thermal bridge, compared to the one dimensional heat flow, both in steady state conditions:

$$Q_{2D} = U_{1D} \cdot A_{Tot} \cdot \Delta T + \Psi \cdot l \cdot \Delta T \quad [W]$$

(5.2)

Where:

$\Psi$ is the linear thermal transmittance of the linear thermal bridge separating the two environments being considered [W/mK];
\( A_{\text{tot}} \) is the total area of the component \([m^2]\);

\( U_{1D} \) is the thermal transmittance of the 1-D component \( k \) separating the two environments being considered \([W/m^2K]\);

\( l \) is the length of the component characterised by the thermal bridge \([m]\);

\( \Delta T \) is air temperature difference between the two environments \([K]\).

In the experimental evaluation \( Q_{2D} \) \([W]\) is given by the mean value measured by each heat flow meter multiplied for its area of influence and \( l \) is 1 meter (width of the mock-up). While the 1-D component is the one to which the conditions of the centre of panel are applied (Figure 5.21).

The \( \Psi \)-value was then calculated from the experimental measurements as follows:

\[
Q_{2D} = HFM_5 \cdot A_1 + HFM_6 \cdot A_2 + HFM_7 \cdot A_3 + HFM_8 \cdot A_4 + HFM_1 \cdot A_5 + HFM_2 \cdot A_6 + HFM_3 \cdot A_7 \text{ [W]} \quad (5.3)
\]
5.4.2 Thermographic analysis (IR)

The thermal bridge is an area of the building envelope with thermal and geometrical properties which varies in respect to the adjacent construction [40]; as a consequence, the temperature of the inner surface will be interested by considerable variations in respect to the undisturbed area, on the contrary an almost constant value of the heat flux and temperature can be considered for the whole undisturbed area. The undisturbed area can be defined accordingly to [33] as the area where the temperature variation is less than 1% of the total variation (Figure 5.22).

![Figure 5.22 – Characterisation of the undisturbed area]

In this undisturbed zone, the surface temperature is a function of the thickness and thermal conductivity of the layers that constitute the wall, of the temperature of the air, and of the surface heat transfer coefficients. In steady-state conditions, the one-dimensional heat flow through the wall can be written as:

\[
Q_{1D} = h_{1D,i} A_{1D} (T_i - T_{1D,is})
\]  
(5.6)

Where \( h_{1D,i} \) is the surface heat transfer coefficient (which takes into account of both convective and radiative heat transfer), \( A_{1D} \) is the area of the wall and the temperature \( T_i \) and \( T_{1D,is} \) represent respectively the air temperature and the wall surface temperature at point \( i \). In the case of the introduction of a thermal bridge in the area \( A_{1D} \), Eq. (6) is not applicable since the temperature is far
from being uniform throughout the entire surface. Analysing the area with an IR camera, the surface thermal field of the undisturbed and disturbed area can be measured, therefore, a temperature value $T_{\text{pixel, is}}$ could be associated to each pixel that is representative of a part of the wall surface ($A_{\text{pixel}}$); the extension of $A_{\text{pixel}}$ depends from the IFOV (instantaneous field of view) of the IR camera, which is dependent on the field of view of the camera and the distance from the measured object, according to eq. (1). Hence, the evaluation of the heat flux is possible in each pixel, obtaining a formulation of the whole area dispersion as:

$$Q_{2D} = h_{tb,i}A_{\text{pixel}} \sum_{p=1}^{N}(T_i - T_{\text{pixel, is}})$$

(5.7)

Where $Q_{2D}$ [W] is the total heat flow with the presence of a thermal bridge. With the hypothesis of constant surface coefficient:

$$h_{1D,i} = h_{tb,i}$$

(5.8)

And being $N$ the number of pixels of the entire area, according to the relation:

$$A_{1D} = NA_{\text{pixel}}$$

(5.9)

The ratio between the total heat flux $Q_{2D}$ and the $Q_{1D}$, defined as $I_{tb}$, *quantitative incidence factor of the thermal bridge* [33] can be written as:

$$I_{tb} = \frac{Q_{2D}}{Q_{1D}} = \frac{h_{tb}A_{\text{pixel}} \sum_{p=1}^{N}(T_i - T_{\text{pixel, is}})}{h_{1D}A_{1D}(T_i - T_{1D, is})}$$

(5.10)

Simply subtracting 1 to $I_{tb}$ and multiplying the result by the heat exchanged through the undisturbed wall $Q_{1D}$, the heat loss due to the thermal bridge is obtained. In the hypothesis of $h_{1D,i} = h_{tb,i}$, that is the surface heat coefficient are constant on the whole area despite the presence of the thermal bridge, it follows:

$$I_{tb} = \frac{h_{tb}A_{\text{pixel}} \sum_{p=1}^{N}(T_i - T_{\text{pixel, is}})}{h_{1D, i}A_{1D}(T_i - T_{1D, is})} = \frac{A_{\text{pixel}} \sum_{p=1}^{N}(T_i - T_{\text{pixel, is}})}{NA_{\text{pixel}}(T_i - T_{1D, is})} = \frac{\sum_{p=1}^{N}(T_i - T_{\text{pixel, is}})}{N(T_i - T_{1D, is})}$$

(5.11)

Therefore only by measuring the surface temperature of the whole component and the air temperature, the $Q_{2D}$, hence the $\Psi$-value, can be calculated. In fact, this quantitative factor could be also expressed in terms of an increase of the thermal transmittance $U_{1D}$ of the undisturbed zone due to the effect of the thermal bridge; considering the influence of the thermal bridge, and using the hypothesis of steady-state conditions, the total value of the wall thermal transmittance $U_{tb}$ can be written as follows:

$$U_{tb} = U_{1D} \times I_{tb}$$

(5.12)
Given that:

\[ U_{tb}(l_{tb} + l_{1D}) = U_{1D}(l_{tb} + l_{1D}) + \psi \]  

(5.13)

\( l_{tb} \) can be written as:

\[ l_{tb} = \frac{U_{1D}(l_{tb} + l_{1D}) + \psi}{U_{1D}(l_{tb} + l_{1D})} \]  

(5.14)

Therefore:

\[ \psi = (l_{tb} - 1)U_{1D}(l_{tb} + l_{1D}) \]  

(5.15)

Where \( l_{1D} \) is the length of undisturbed zone, and \( l_{tb} \) is the length of the disturbed zone corresponding to the distance from the thermal bridge equal to 99% of the total temperature difference measured along the \( l_{1D} \).

The hypothesis \( h_{1D,i} = h_{tb,i} \) limits the applicability of this method to the case of spatial uniformity of value of the heat transfer coefficients in presence of the thermal bridge. The surface heat transfer coefficient is composed of a convective component and of a radiative one [37]:

\[ h = h_c + h_r \]  

(5.15)

\[ h_r = 4F_{\alpha} \sigma \left( \frac{T_{ur} + T_{pr}}{2} \right)^3 \]  

(5.16)

Where \( T_{pr} \) is the plan radiant temperature, calculated by means of the view factors between the mock-up and the climatic chamber, which can be considered constant in time (due to the temperature regulation in the climatic cell) and along the thermal bridge (maximum distance between the thermocouples on the mock-up is 50 cm). Given that \( T_{ur} \) (surface temperature) is not constant along the thermal bridge, \( hr, hc \) and hence \( h \) may not be constant. Therefore this hypothesis deserves further investigation.
5.5 Results

5.5.1 Heat flows and temperatures

During the HFM measurements two rounds of tests were carried out and this was useful in order to evaluate the repeatability of the $\Psi$-value measurements by means of the climatic chamber. During the two tests the chamber environmental conditions were kept the same except for the curtain position in the cold box, from 0.70 m far from the mock-ups in the first tests to 1.30 m distance in the second tests. The heat flux and temperature measurements on the mock-ups surface are shown in the following graphs for the two tests (from Figure 5.23 to Figure 5.26).

**Figure 5.23** - WING design: values of the heat flow meters a) and of the surface thermocouple b) in the two rounds of tests

**Figure 5.24** - HYP&R DC design: values of the heat flow meters a) and of the surface thermocouple b) in the two rounds of tests
The two rounds of tests gave almost similar results especially regarding the surface temperatures. Due to the uniformity of boundary conditions, the difference between the two round of tests with the HFM method are representative of the inaccuracy of such a characterization. This is not due to the experimental methods adopted, but to relatively high inaccuracy of Eko heat flux meters compared to Hukseflux, and because the high resolution of measurement needed to analyse the effect of this kind of thermal bridge. Although the Eko heat flux meters represented the best option in terms of accuracy and size, commercially available, for the resolution of measurements needed. From Figure 5.23 to Figure 5.26 the effect of the thermal bridge on each design can be noticed. The disturbed area usually ends before the fifth sensor (16 cm) correspondent to the first Hukseflux sensor Therefore it can be considered that the last three sensors (at 16, 30 and 50cm) belong to the undisturbed area (one dimensional heat flow). In the undisturbed area that is what we consider as centre of panel, the
conditions are equal for all the mock-ups: the heat flow (mean value between the sensors placed at 16, 30 and 50cm from the edge) is approximately 40W/m², the $T_{OUT}$ is 20°C and the $T_{IN}$ is 38°C. Therefore the measured conductance value $C$ is equal to 2.3 W/m²K where $C$ is defined as:

$$C = \frac{q}{\Delta T_S} \left[ \frac{W}{m^2K} \right]$$ (5.17)

And by adding the external and internal heat transfer coefficients according to the ISO 6946:2007 [41], the U-value at the centre of panel is equal to 1.6 W/m²K. This measurement can be taken as verification for the experimental apparatus, as it confirms the U-value declared by the production as U-value cop (centre of panel) for the glazing provided.

In both HYP&R mock-ups a peculiar trend of the heat flow can be noticed (Figure 5.24_a and Figure 5.25_a). It was expected that the heat flow density would have decreased monotonically with the distance from the connection. Instead, in these two mock-ups, the heat flow density near the edge of the glazing (area between the frame and the centre of panel) is lower than the one in the centre of panel. This is due to the additional thermal resistance given by the frame that decreases the heat flow in this area compared to that one in the centre of panel where the thermal resistance is only given by the DGU. This is confirming the first numerical results given by the FEM model (i.e. edge U-value lower than cop U-value) obtained for the HYP&R and TWIST design options. This effect is not reflected by the surface temperature profiles (Figure 5.24_b and Figure 5.25_b), therefore it is expected that will be present a bigger difference between $\Psi$-values observed with the IR method compared to the HFM.

5.5.2 Surface heat transfer coefficient values

The surface heat transfer coefficients along the mock-up were calculated according to the EN/ISO_6946:2007 as follows [41]:

$$h_{OUT/IN} = \frac{q_i}{(T_{SOUT/AIN} - T_{AOUT/SIN})} \left[ \frac{W}{m^2K} \right]$$ (5.18)

Where $Q$ [W/m²] is the heat flow detected by each heat flow meter $i$, $T_{Sout}$ is the surface temperature on the outside facing surface placed at the same height of the $i$ heat flow meter and $T_{Aout}$ is the air temperature of the outside (same definition on the inside for $T_{Sin}$ and $T_{Ain}$). As only one heat flow meter was placed in the inner side, just one value (corresponding to the centre of panel) of $h_{IN}$ will be calculated.
These results should be particularly useful in order to validate the FEM thermal model, and to validate the previously mentioned hypothesis of surface heat transfer spatial uniformity.

Figure 5.27 - Values of the outdoor surface coefficient for each design along the cross section during both tests

Figure 5.27 shows the results of the total surface coefficients in relation to the temperature difference between surface and air in the cold chamber, calculated for all the mock-ups in both tests. Taking into account the accuracy of the measurements of the surface heat transfer coefficients (± 1 W/m²K), it is not possible to consider the surface coefficients as varying along the thermal bridge. Although some exceptions can be seen in the two TWIST tests, in which the surface heat transfer coefficients present an evident trend, increasing towards the thermal bridge (from 8 to 14-15 W/m²K). In all the other cases the surface heat transfer average coefficients can be considered between 7 and 9 W/m²K ± 1 W/m²K. The average value is given by ISO 6946:2007 [41] for internal surface heat transfer coefficient is 8 W/m²K.

This observation means that the hypothesis of $h_{1D,i} = h_{tb,i}$ made for the IR method [33] can be verified, except for the TWIST design, in which the measured $hi$ for each sensor need to be used for the calculation of the $Ψ$-value with the IR method. Moreover considering the surface values as constant will lead to a considerable simplification during the forthcoming validation of the FEM model since a single boundary condition is required rather than multiple boundary conditions along the mock-up section.
5.5.3 IR Temperature measurements

The results of the IR temperature measurements on the mock-ups surface are shown in the following graphs (Figure 5.28 to Figure 5.31, the area selected for measurements are highlighted in red):

Figure 5.28 - OUT Surface temperature trend on WING mock-up and thermal image

Figure 5.29 - OUT Surface temperature trend on HYP&R DC mock-up and thermal image

Figure 5.30 - OUT Surface temperature trend on HYP&R Sika mock-up and thermal image
As far as the surface temperatures are concerned, the IR method gave similar results compared to the temperature measured by the thermocouples in the HFM analysis (from Figure 5.23 to Figure 5.26). In the undisturbed area the temperature is around 19°C for WING and HYP&R DC mock-ups and 20°C for TWIST and HYP&R Sika mock-ups. In the surface temperature trend of the HYP&R DC mock-up is possible to notice a peculiar trend similar to the one measured by the heat flow sensors in Figure 5.24 a), therefore it is expected that the difference between Ψ-values observed with the IR method compared to the HFM will be minimal.

5.5.4 Ψ-Values

In Figure 5.32 the Ψ values calculated with both HFM and IR methods are shown. Similar measured Ψ-values by means of the two methods can be noticed. Such low Ψ-values mean that the thermal bridge does not affect in a significant way the overall thermal performance of the whole unitized system, but it also implies that it is difficult to quantify the Ψ-value, as the accuracy of the measurements is almost of the same order of the results (around ± 0.020 W/mK), and this can be noticed especially form the two HYP&R designs. In the two HYP&Rs indeed the difference between the Ψ-values measured in the two HFM tests is higher compared to the other designs, in which the Ψ-values gave almost similar results in both tests.

The higher deviation between HFM and IR results is found in the TWIST design option: this is due to the assumption of constant heat surface coefficient made in the IR method, which cannot be verified in the TWIST design as seen in section 5.5.2
Figure 5.32 - $\Psi$-values calculated with HFM and IR methods. Two rounds of tests results are shown for the HFM method including the accuracies of the measurements.
5.6 Comments to the results

From the experimental analysis it is confirmed that the HYP&R design options perform better than the other design options from the point of view of a lower U-value. For the TWIST design options, the simulations suggested lower $\Psi$-values than the one measured. This difference is mainly due to the simplified convective heat transfer model used in the FEM software, for the closed cavity of the TWIST frame. The WING design option presents $\Psi$-values which are comparable with the simulations but in the middle in terms of $\Psi$-value between the other three design options. In general the WING design option was found to be a good compromise in terms of thermal performance between the four possible options. In fact although the $\Psi$-value is not the lowest, it is in any case quite low, while ensuring a really thin frame (more aesthetical value), lower condensation risk and lower risk of decreased structural performance due to temperature increase in the connection.

5.7 Characterisation of CW thermal performance during building service life

The characterisation of CW thermal performance by means of the Infrared Camera was found to be a less intrusive method. Indeed following the Asdrubali approach [33], it is possible to determine the U-values and $\Psi$-values only relying on the surface temperatures detected by the camera. On the other hand for the characterisation by means of HFM method more sensors are required (heat flow meters and thermocouples) and all of them have to be connected to a Datataker through wires. Given the similar results between IR and HFM method (Figure 5.32), at least for most of the design options, it is possible to suggest that using an Infrared Camera would be the best solution for the thermal characterisation of building façades during their service life (as only one sensor is needed). Still the approximation on which the IR method relies (constant heat surface coefficient along the profile) cannot be verified for all the design options, leading to different results between HFM and IR method (see TWIST design option). For a reliable thermal characterisation using the IR camera, at least two heat flow meters should be needed: the first one to evaluate the heat flow on the area affected by the thermal bridge and the second one on the undisturbed area. In this way $h_{tb}$ and $h_{ID}$ can be quantified and if the assumption of $h$ constant along the profile is not verified, it will be anyway possible to quantify the $I_{tb}$ according to the equation (5.10).
6. VALIDATION OF THE NUMERICAL MODEL

The aim of the validation is to obtain a simulation model that can represent results as close as possible to the reality. Once the model is validated, the thermal performance of the different systems can be tested under several boundary conditions and the desired modifications can be deployed in order to evaluate the effective improvements on the overall performance.

The validation of the model consists in the comparison between the results obtained with the FEM analysis and those measured by means of the experimental analysis. To this purpose the models analysed in chapter 4 were modified according to the actual mock-ups tested and the same boundary conditions measured in the climatic cell were applied.

As far as the DGU is concerned an aluminium spacer was adopted according to the producer specifications [42]. The dimensions of the spacer are 11.5 x 6.6 mm and 0.4 mm thickness. As there were no further specifications for the primary and secondary sealant used in the DGU, the simulation model adopted PIB as primary sealant (λ = 0.2 W/mK) and silicone as secondary sealant (λ = 0.3 W/mK).

6.1 Comparison with the experimental results

The conditions measured during the test of each mock-up (air temperature and surface heat transfer coefficients) were applied to the correspondent simulation model as boundary conditions. A table of the boundary condition used for the different design options is shown in Figure 6.1.

As discussed in section 5.5.2, taking into account the accuracy of the measurements of the surface heat transfer coefficients (± 1 W/m²K), the variation of the calculated values along the cold side of the profile is not relevant for the majority of the design options, and the hypothesis of constant $h_{tot}$ can be assumed [33]. Anyway, a higher value of $h_{tot}$ was usually measured in the area disturbed by the thermal bridge (especially as far as the TWIST design was concerned). For this reason two round of simulation were performed using two different methods:

- Method A: a unique surface coefficient is applied along the cold surface, calculated as the average value among the results given by the seven heat flow meters positioned on the component surface in the experimental analysis.
- Method B: two different surface coefficients are used. The first is applied on the area mainly disturbed by the thermal bridge (the first two centimetres, correspondent to the first Eko heat flux meter). In particular the total surface coefficient is divided into his radiative and convective components. The radiative coefficient $h_{r*}$ was calculated as stated in eq. 5.16, and
the convective coefficient is the difference between $h_{inc}$ and $hr^*$. The surface coefficient applied on the rest of the profile is an average between the values calculated from the other six heat flux meters employed.

In both methods the surface coefficient applied on the warm side is the same along the profile and it is the one measured in the centre of panel by means of the only heat flow meter used on that side during the experimental analysis.

![Diagram of two methods](image.png)

**Figure 6.1 – Application of climatic cell boundary conditions to the simulation software, two different methods**

<table>
<thead>
<tr>
<th></th>
<th>Method A</th>
<th>Method B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$T_{in}$ [°C]</strong></td>
<td><strong>$H_{in}$ [W/m$^2$K]</strong></td>
<td><strong>$T_{out}$ [°C]</strong></td>
</tr>
<tr>
<td>WING</td>
<td>41.2</td>
<td>11.4</td>
</tr>
<tr>
<td>HYP&amp;R DC</td>
<td>40.9</td>
<td>10.7</td>
</tr>
<tr>
<td>HYP&amp;R Silica</td>
<td>41.1</td>
<td>12.8</td>
</tr>
<tr>
<td>TWIST</td>
<td>41.2</td>
<td>15.1</td>
</tr>
</tbody>
</table>

6.1.1 Surface Temperatures

In the following figures (Figure 6.2 to Figure 6.9) the trend of the surface temperatures resulting from both methods is directly compared to the values measured by the thermocouples in the BET cell.
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Figure 6.2 – WING design: Trend of surface temperatures obtained with the two simulation methods compared with the BET cell measurements

Figure 6.3 – WING: Temperature difference between FEM and experimental analysis obtained with both methods
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Figure 6.4 – HYP&R DC993 design: Trend of surface temperatures obtained with the two simulation methods compared with the BET cell measurements

Figure 6.5 – HYP&R DC: Temperature difference between FEM and experimental analysis obtained with both methods
Figure 6.6 – HYP&R SikaMove design: Trend of surface temperatures obtained with the two simulation methods compared with the BET cell measurements

Figure 6.7 – HYP&R Sika: Temperature difference between FEM and experimental analysis obtained with both methods
Figure 6.8 – TWIST design: Trend of surface temperatures obtained with the two simulation methods compared with the BET cell measurements

Figure 6.9 – TWIST: Temperature difference between FEM and experimental analysis obtained with both methods
From the previous figures it is clear that the temperature values in the undisturbed area are the same in both FEM and experimental analysis. On the other hand, using the Method A, the difference between the FEM values and the experimental ones is high in the area influenced by the thermal bridge (between 5 and 6 °C for all the design options), both internally and externally. In method B, the use of a specific surface coefficient in the disturbed zone, sensibly reduced the difference between experimental and FEM results for surface temperature on both sides. For all the design options the $\Delta T$ goes from 5÷6°C to 1÷2°C as maximum. As far as the WING and TWIST design are concerned (Figure 6.3 and Figure 6.9) the temperatures obtained with Method B deviate no more than 1°C from the measurements in the climatic cell. In the HYP&R designs, even if the method B gives better results than method A, the FEM temperatures are still different from the experimental values (Figure 6.5 and Figure 6.7), especially on the stainless steel frame. This is due to the assumption of the same heat transfer coefficient on frame and centre of panel on the warm side. The frame indeed has a sensibly lower emissivity compared to the centre of panel that leads to a smaller radiative heat transfer and consequently to a lower $h_{tot}$. For this reason the frame temperature of the HYP&Rs in the FEM analysis are higher than those measured in the cell. In the TWIST design option, the use of the same $h$ for frame and centre of panel gave anyway good results due to the geometry of the profiles: these two design options are characterised by a metal extrusion that dissipates more heat compared to the HYP&R plate.

Method C

Given the results of the previous analysis a third method is introduced. In the FEM analysis the surface temperature of the frame on the warm side was resulting higher than the experimental values, especially as far as the HYP&R design options were concerned. The reason can be found in the adoption of the same surface coefficient for frame and centre of panel. As the frame has a lower emissivity compared to the centre of panel (0.26 against 0.84) less heat is dissipated by radiation, therefore the frame should be characterised by a lower heat transfer surface coefficient. Method C is an approximate approach in which the frame surface coefficient of each design option is reduced of 3W/m$^2$K (radiative component) compared to the centre of panel: this value was chosen considering that the calculated $h_r$ in the experimental analysis (equation 5.16) was about 5W/m$^2$K at the centre of panel. For the cold side the same approach of method B was used. The temperature difference between FEM results and Experimental results is shown in Figure 6.10. As expected, in the HYP&R designs, the frame temperatures reached values close to those of the experimental analysis. In these design options also the temperature difference on the cold side decreased. On the other hand the adoption of a lower surface coefficient drastically reduced the frame
temperatures on the WING design option. This is due the design geometry simulated: in the FEM analysis the frame of WING design is considered as a 30mm plate, while the actual design is characterised indeed by a steel wing connected to the plate by means of hinges (point elements). Therefore the temperatures on the frame plate are conditioned by the metal wing extrusion even when there is no direct connection through the hinges.

Figure 6.10 - Temperature difference between FEM and experimental analysis adopting Method C

In Figure 6.11 the results obtained with the three methods are summarised and compared. The graphs represent the total difference between surface temperatures calculated by experimental analysis and FEM analysis, both on the cold (OUT) and the warm (IN) side: the figures represent the combined mean square values of the temperature difference.

\[
Total \Delta T = \sqrt{\Delta T_{y1}^2 + \Delta T_{y2}^2 + \Delta T_{y3}^2 + \Delta T_{y4}^2 + \Delta T_{y5}^2 + \Delta T_{y6}^2 + \Delta T_{y7}^2}
\]  

(6.1)

Where:
$\Delta T$ is the surface temperature difference between calculated results (FEM model) and experimental values (Bet cell);

$Y_n$ refers to the position where the surface temperature was detected along the profile (starting from the thermal bridge to the centre of panel).

As far as the cold side is concerned, the choice of detailed surface coefficients (method B and C as well) resulted to be the more suitable for all the design options. Method C further improved the results in the HYP&R designs compared to Method B.

Regarding the warm surface, the HYP&R design options sensibly beneficed by using specific surface coefficients at the frame level. The same trend appears for the TWIST design even if with a lower incidence, indeed the inside temperatures on the TWIST are already similar to the experimental adopting a constant surface coefficient (method A), but in any case method B and C further improved the difference between simulation and experiments.

The WING design option is the only exception to the common trend: the inside surface temperature reach values similar to the experimental ones using the method B, but consequently deviate more while using method C for the reason explained before. In this case the adoption of the same internal surface coefficient along the profile has to be preferred.

![Figure 6.11 – Surface temperature difference between experimental results and FEM results using method A, B or C: combined mean square values](image)
6.1.2 Thermal Bridge effect

The evaluation of the thermal bridge was conducted as for the experimental analysis on half of a 1x1m panel (total area 0.5m$^2$) according to the following equation [40].

\[
Q_{2D} = U_{1D} \cdot A_{Tot} \cdot \Delta T + \Psi \cdot l \cdot \Delta T \quad [W] \tag{6.2}
\]

Where:

- \( \Psi \) is the linear thermal transmittance of the linear thermal bridge separating the two environments being considered [W/mK];
- \( A_{tot} \) is the total area of the component [m$^2$];
- \( U_{1D} \) is the thermal transmittance of the 1-D component \( k \) separating the two environments being considered [W/m$^2$K];
- \( l \) is the length of the component characterised by the thermal bridge [m];
- \( \Delta T \) is air temperature difference between the two environments [K].

\( Q_{2D} \) [W] is given by the transmittance value of the disturbed and undisturbed zone (respectively named as Frame and COP) multiplied for the corresponding areas of influence and \( \Delta T \). The thermal bridge length \( l \) is 1 meter. While the 1-D component is the one to which the conditions of the centre of panel are applied. The considered disturbed and undisturbed areas were the same of the experimental analysis: the first 10 cm were evaluated as influenced by the thermal bridge, and the other 40cm as centre of panel. The \( \Psi \)-value was then calculated from the THERM results as follows:

\[
Q_{2D} = (U_{frame} \cdot A_{frame} + U_{COP} \cdot A_{COP}) \cdot \Delta T \quad [W] \tag{6.3}
\]

\[
Q_{1D} = U_{COP} \cdot A_{Tot} \cdot \Delta T \quad [W] \tag{6.4}
\]

\[
\Psi = \frac{Q_{2D} - Q_{1D}}{\Delta T \cdot l} \quad [W/mK] \tag{6.5}
\]

Moreover the \( I_{tb} \), quantitative incidence factor of the thermal bridge [33] was calculated as:

\[
I_{tb} = \frac{Q_{2D}}{Q_{1D}} \tag{6.6}
\]

In Figure 6.12 the \( \Psi \)-value, the heat flow (\( Q_{2D} \)) and the \( I_{tb} \) (as defined in Eq 5.11) resulting from methods A, B and C of the FEM analysis are compared to the values calculated by means of the climatic cell, and the uncertainties due to the software (for the FEM methods) and to the measurement apparatus (for the experimental analysis) are shown through error bars.
As the linear thermal transmittance is found to be an extremely low value, the difference between FEM and experimental results is relatively high (especially as far as the HYP&R designs are concerned) even if the absolute difference is not excessive (0.07 W/mK for HYP&R DC). For this reason the deviation values to be considered are those corresponding to the heat flow and to the \( I_{tb} \).

For all the design option is clear how the adoption of method A gives results closer to the experimental analysis. In WING and TWIST design, while using method A, both \( I_{tb} \) and heat flow do not deviate more than 3%, which is a very low value considering the accuracies of the software (around 1%) and of the experimental apparatus (5% for the heat flow meters). In the two HYP&Rs the deviation is higher but still acceptable as far as method A is employed, indeed the heat flow difference between
FEM and experiments is only 2.4W/m² for the HYP&R DC and 1.7W/m² for the HYP&R Sika. This difference may be due to the uncertainties related to unknown modelled component properties (spacer thermal properties).

Therefore, as far as the overall thermal performance of the panel is concerned, using an average surface heat transfer coefficient along the profile (method A) gave results closer to the values measured by means of the BET cell. On the other hand the adoption of method B and C gives the opportunity to better describe the local surface temperatures especially on the cold side.

The parameters to be considered for the evaluation of thermal performance of the design options are the total transmittance value, the Ψ-value and the lowest temperature reached on the warm surface for the assessment of the condensation risk. Consequently, method A is to be considered more suitable to the aim of assessing total U-values and Ψ-values, while an adoption of different surface coefficients along the profile (method B and C) would be preferred for the condensation risk assessment.
6.2 Improvement of the original designs

After the successful comparison with the experimental results, the simulation model can be considered as validated. In this chapter the S+G design options are simulated again using THERM 7.2 Applying CEN boundary conditions [37]:

- External conditions: Temperature = 0°C, Film coefficient = 23 W/m²K;
- Internal conditions: Temperature = 20°C, Film coefficient for glass = 8.02 W/m²K, Film coefficient for frame = 7.71 W/m²K;
- Relative Humidity : 50%;
- Edge of the glass length (distance from frame in order to have undisturbed one dimensional heat flow) : 190 mm;

In addition to the Schüco UCC SG another state-of-the-art detail was studied as reference for the thermal performance values: Forster Thermfix Vario (externally capped and thermally broken system) [19]. The details studied are shown in Figure 6.13.

![Fig. 6.13 - Different design options studied with dimension stated](image)

Three different spacers (with increasing thermal performance) were adopted in the simulation in order to quantify the improvement due by the use of lower conductive materials in the double glazing unit (DGU), and the sensitivity of the thermal performance of the connection on the spacer adopted. In Figure 6.14 the features of the spacers adopted are shown: the first one is an aluminium spacer with the same specifications of the one used for the mock-ups in the BET cell. The second spacer is made of steel (less conductive than aluminium) and the primary sealant used is thicker than the one used in
the first spacer. The last one is a thermoplastic spacer (TPS) [43] which is one of the best performing typologies as far as the thermal performance is concerned [24].

![Figure 6.14 – Three different spacers used in the simulations: aluminium spacer, steel spacer and thermoplastic spacer](image)

6.2.1 Total transmittance values and $\Psi$-values:

The total transmittance values [W/m²K] (defined in section 4.2) for a 1.5x3.5m are shown in Figure 6.15. The double glazing unit (DGU) was simulated as well without frame and used as reference to quantify the influence of the frame itself on the curtain wall unit. In all the design options the use of a better spacer improved the U-value by 8% (WING and TWIST) down to 3.7% (Forster). The WING design has a higher transmittance value compared to the other S+G options, anyway is comparable to the one of the Schüco UCC. The adoption of TPS spacer resulted in extremely low U-values considering that the DGU is characterised by a $U_g = 1.63$ W/m²K at the centre of panel.

It has to be considered that in the case of the TWIST design option, a simplified model was used for the convective heat exchange in the closed frame cavity due to FEM software limitations. This could result in inaccurate (overestimated) performance estimation of TWIST design.
In Figure 6.16 the effect of the frame of the different design options on the total U-value is shown. This value was evaluated by direct comparison with the DGU total transmittance and it represents the increase of U-value due to the frame only. It is clear that the effect of the frame on the U-value of the panel is extremely low in all the design especially when a TPS spacer is adopted. In the TWIST and the two HYP&Rs the increasing of the total U-value (compared to the DGU only) is of the order of 0.1W/m²K even in the worst condition (aluminium spacer). It has to be noted that in the Forster option, the effect of the frame has not sensibly varied while using better performing spacers. This is due to the frame capped design, indeed the stainless steel cap on the exterior side and the EPDM protection on both sides of the DGU allow to decouple the effect of the spacer with the total thermal performance of the frame.

It is noted that in structural glazing system the U-value is more sensitive to the choice of the spacer, especially in WING design option, due to the thin frame and the large metal fin.
The linear thermal transmittance \([\text{W/mK}]\) was calculated as described in section 4.5.3 according to the EN/ISO 10211-1 [40], where \(\Psi\) is the additional heat flow across the sections by meter length and one degree temperature difference due to the thermal bridge, compared to the one dimensional heat flow, in steady state conditions. The \(\Psi\)-values calculated compared to the spacer variability are shown in Figure 6.17. These values allow a direct comparison of the connection thermal performance per unit length. The best designs in terms of thermal energy efficiency, according to this analysis, are the HYP&R and TWIST design options (up to 30% improvement compared to the Schüco reference), while the WING options reaches the same level of performance of the Schüco UCC. Also in this case, for all the design options the performance was sensibly enhanced by the use of a less conductive spacer (51% improvement in the WING and 54% in the TWIST from the aluminium spacer to the TPS spacer). For the reasons explained before the performance of Fonster detail is not affected by the use of a better spacer, indeed the TPS spacer adoption only improved the \(\Psi\)-value of 24%, which is sensibly lower than the improvement reached by the other design options.

The small \(\Psi\)-value difference between the aluminium and the stainless steel option for in the Schüco design, means that a lower conductive metal per se is not essential, if the design is optimised, but the geometry can be a higher influencing factor.
6.2.2 Condensation risk assessment

*Figure 6.18* shows the variability of the lowest indoor surface temperature in each design option due to the different design alternatives. The surface temperature should be higher than the dew point temperature to avoid condensation, that for indoor air temperature at 20°C and relative humidity of 65% is equal to 13.2°C [38].

As the HYP&R designs and the WING present point elements (2 rotules per meter for the HYP&R and 4 hinges per meter for the WING), the lowest temperature was calculated also in the sections free from the extrusions (last three elements in *Figure 6.18*), where the curtain wall frame only consists of a stainless steel plate.

In the S+G design options, the lowest temperature is always observed close to the connection between two different panels, where the frame and adhesive meet the glass (red points in *Figure 6.18*).

From the results it is possible to see that using a better performing spacer results in an increased lowest temperature, indeed the enhancement of the temperature is up to 2-3 °C in all the design options.

Nevertheless in the WING and HYP&R designs, the lowest temperature is always below the dew point in the sections where there is not any hinge (WING) or any rotule (HYP&R): even adopting a TPS spacer the lowest temperature is lower than 13.1°C. Meanwhile in the TWIST design option, using a stainless steel spacer is enough to achieve the wet bulb temperature at 13.2°C.
An improvement in the design of the connection between two panels is needed in order to protect the uncovered area which is more sensible to the external temperatures and therefore avoid condensation (an example was described in section 4.6 for the TWIST design).

Figure 6.18– Lowest surface temperature reached over the variability of spacer used. Reference designs values highlighted in red. The location of the minimum temperature is pointed in the drawings
7. SOLAR RADIATION ANALYSIS

The primary sealant and structural adhesives used for the S+G connections may be sensible to high temperatures (more than 60 °C). The higher the temperature the lower their structural integrity, which could eventually lead to melting of the primary sealant, outgassing from the glazing cavity and condensation of water vapour inside the glazing cavity [4]. For this reason an appropriate evaluation of the temperature increase in the materials in the connections is required. For this aim the worst case scenario for higher temperature in the connection must be evaluated.

7.1 Worst case scenario for different climates

Three possible building locations (characterised by different climates [44]) were considered in order to evaluate the worst case scenario as far as the solar radiation is concerned: Rome, London and Helsinki. The effect of the solar radiation can vary due to different orientation and inclination of the façade, for this reason two possible employments of the curtain wall system were analysed: façade (90° tilt) and roof (0° tilt).

When a wall is hit by solar radiation of intensity $I$ (W/m$^2$), the wall partially absorbs the incident energy according to its absorption coefficient “$\alpha$” producing a rise in temperature of the surface itself. The solar-air temperature ($T_{\text{sol-air}}$) is the fictitious temperature of the outdoor air which, in the absence of solar radiation on the outer surface of the roof or wall, would give the same rate of heat transfer through the wall or roof as the actual combined heat transfer mechanism between the sun, the surface of the roof or wall, the outdoor air and the surroundings. It is defined as:

$$ T_{\text{sol-air}} = T_{\text{air}} + \frac{\alpha \cdot I}{h_e} \ [^\circ C] \quad (7.1) $$

Where:
- $T_{\text{air}}$ is the external air temperature [°C]
- $\alpha$ is the absorbance of the façade [-]
- $I$ is the incident solar radiation [W/m$^2$]
- $h_e$ is the external surface heat transfer coefficient [W/m$^2$K]

The evaluation of the maximum $T_{\text{sol-air}}$ over the year determines the worst case scenario for each location in both applications. During the calculations $\alpha=0.2$ and $h_e = 23$ W/m$^2$K were used. The solar radiation incidence was analysed for different façade orientations considered more exposed to the solar radiation during the day: South-East, South, South-West and West. The European
commission website PVGIS (Photovoltaic Geographical Information System) was used as database for the solar radiation and external temperature values.

In *Figure 7.1* an example of the Tsol-air temperature trend over the year is shown (Rome example for a façade at 90° tilt). In ANNEX 2 the values of the solar incidence and of the calculated Tsol-air for all the conditions considered are detailed. As the $\alpha$ of a glazing façade is lower if compared to an opaque element, the $T_{\text{sol-air}}$ in this case mostly depends by the external air temperature.

Once the max Tsol-air has been estimated, the solar incidence and the external air temperature correspondent to that value are considered for the worst case scenario. In *Table 7.1* these values are defined.

![Graphs showing trend of max Tsol-air over the year for different orientations and correspondent values of I and Tair: Rome example, 90° tilt façade](image)

**Table 7.1** – I and $T_{\text{air}}$ values considered as worst case scenario for the three different climates at both tilts

<table>
<thead>
<tr>
<th>90° Tilt</th>
<th>WORST CASE SCENARIO</th>
<th>I [W/m²]</th>
<th>Tair [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-West orientation</td>
<td>August ROME</td>
<td>643</td>
<td>30,4</td>
</tr>
<tr>
<td></td>
<td>July LONDON</td>
<td>708</td>
<td>20,6</td>
</tr>
<tr>
<td></td>
<td>July HELSINKI</td>
<td>816</td>
<td>18,4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0° Tilt</th>
<th>WORST CASE SCENARIO</th>
<th>I [W/m²]</th>
<th>Tair [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>July ROME</td>
<td>909</td>
<td>30,4</td>
</tr>
<tr>
<td></td>
<td>July LONDON</td>
<td>807</td>
<td>20,8</td>
</tr>
<tr>
<td></td>
<td>July HELSINKI</td>
<td>804</td>
<td>18,5</td>
</tr>
</tbody>
</table>
7.2 Solar radiation effect with THERM software

The FEM software used (THERM 7.2) can only evaluate the effect due to the solar radiation in an approximated way and the adoption of a simplified model is required.

Considering as example the façade (90° tilt) being placed in Helsinki, the maximum value of solar radiation is during July for a South West facing surface: I= 816 W/m² (T_{OUT} = 18.4°C, T_{IN} = 26°C).

These conditions were applied as worst case scenario. As it was not possible to directly simulate the solar radiation effect using THERM 7.2, two different approaches were studied in order to understand how the solar radiation affects the components.

The first method consists in calculating the temperatures reached on each layer of the glazing with WINDOW 7.2 (Figure 7.2), in which is possible to consider the effect of the solar radiation, and consequently using those temperatures as boundary conditions in THERM 7.2.

![Figure 7.2 – WINDOW software (LBNL): solar temperature reached in the glazing](image)

The second approach consists in applying a constant flux layer (F) as external boundary condition; the intensity of the flux was equal to the intensity of solar radiation multiplied for the calculated total solar energy transmission of the glazing, g-value, defined as [45]:

\[
g = T_{sol} + \sum n_i A_{sol,i} = T_{sol} + n_1 A_{sol,1} + n_2 A_{sol,2} =
\]

\[
= T_{sol} + \frac{v}{n_e} A_{sol,1} + \frac{v}{(\frac{1}{n_e} + \frac{n_f}{n_g} + R_{car})} A_{sol,2} \quad [-]
\]

(7.2)

Where T_{sol} (total solar transmission coefficient of the DGU), A_{sol,1} (absorbance of the first layer) and A_{sol,2} (absorbance of the second layer) were calculated by means of WINDOW. Moreover s_g and \lambda_g are
respectively the thickness and conductivity of the glass and $R_{cav}$ is the thermal resistance of the cavity. The resulting g-value for the considered DGU is equal to 0.471.

The results of these two methods are shown in Figure 7.3. The HYP&R SikaMove design was taken as example case as it represents the worst possible design option as far as high temperatures are concerned, due to the low U-value of the frame and to the large area of the frame itself.

With the first method a temperature of 65°C is reached on the adhesive surface, while with the second method a temperature of around 28°C is measured on the same points. As the difference between the two approaches is quite large (about 37°C) and the highest temperature calculated is higher than the 60°C threshold, therefore further analysis using different software (Comsol Multiphysics) is required. In any case the first approach appears to give more appropriate results. A first estimate suggests that the highest temperature is reached always in the primary sealant on face 3 of the DGU, and it is close to the limit of applicability of primary sealants for residential applications [4], i.e. 60°C. Therefore the employment of primary sealant (butyl rubbers) for commercial applications is always suggested in the case of S+G design options.

![Figure 7.3 - Results of the temperature reached in the CW system (HYP&R SikaMove) with both methods](image-url)
7.3 Solar radiation effect by means of COMSOL Multiphysics

A detailed analysis of the influence of the solar radiation on the temperatures reached in the curtain wall system was developed by means of the software COMSOL Multiphysics [46]. The incident solar radiation was split into four different components as shown in Figure 7.4 that take into account the transmission, absorption and reflectance phenomena proper of the double glazing unit.

\[
S_1 = I \cdot A_{\text{Sol,1}} \cdot \eta_1 \\
S_2 = I \cdot (1 - \rho_1) \\
S_3 = I \cdot A_{\text{Sol,2}} \\
S_4 = I \cdot A_{\text{Sol,2}} + I \cdot \tau_1 \cdot (1 - \rho_2)
\]

The simulation in COMSOL was performed for the HYP&R SikaMove under the different climates conditions. Three case study were considered:

1) Façade with 90° tilt, at interior air temperature \(T_{\text{IN}} = 26^\circ\text{C}\) (suggested air temperature for summer conditions [47])

2) Façade with 90° tilt, at interior air temperature \(T_{\text{IN}} = 32^\circ\text{C}\) (overheating temperature that can be reached in summer conditions while the air conditioning is switched off)

3) Roofing with 0° tilt, at interior air temperature \(T_{\text{IN}} = 32^\circ\text{C}\)

The temperatures reached in the different details were analysed along three cross-section highlighted in Figure 7.5. Section A-A' aims to define the maximum temperature reached in the unit, section B-B' is needed in order to quantify the temperatures in proximity of the primary sealant and section C-C' is to ensure that the temperature difference inside the glazing does not exceed 40°C (over which value the differential thermal deformation in the glass itself could compromise the structural performance of
the glazing unit [16]). All three sections could give worst case boundary conditions to the structural analysis in order to evaluate the stresses in the different components due to differential thermal expansion. An example of thermal imaging obtained with the software for the first case study is shown in Figure 7.5.

In the following figures (Figure 7.6 to Figure 7.8) the temperature trend along the defined sections is shown. In the roof application (0° tilt, Figure 7.8) the worst conditions are reached: the temperature close to the primary sealant in Rome is higher than 60°C which means that the DGU structural performance would be compromised. For the other two applications (90° tilt) the worst case scenario is represented by Helsinki environmental conditions. In these cases the temperature in the primary sealant does not exceed 55°C which is still within the recommended limit. Anyway the adhesive temperature goes up to 64 °C when considering $T_{IN}=32°C$ (Figure 7.7).

In all the environmental conditions and case studied the temperature difference in the glazing does not exceed 40°C.
7.4 Comparison between the two software results

Comparing the results obtained with the detailed analysis in COMSOL for the Helsinki conditions (90° tilt and T_{IN}=26°C, Figure 7.5) to the results of the two simplified method performed with THERM (Figure 7.3), it is clear that the first THERM method represents a better solution to describe the radiation phenomenon rather than the second method.
Moreover the temperatures reached in the THERM model are higher compared to the COMSOL detailed model (Figure 7.9). This means that if a safety factor has to be considered, the first THERM simplified model could be adopted.
8. DISCUSSION AND FUTURE PERSPECTIVES

Different thermal performance needs to be compared; therefore a rating system is elaborated, shown in Figure 8.1:

![Figure 8.1 - Thermal performance rating of the different design options](image)

The rating of the total U-values was evaluated considering all the configurations of the design options: with aluminium, stainless steel or thermoplastic spacer. The rating was done considering the difference between the best performing option (TWIST with TPS spacer) and the worst one (Schüco with aluminium frame and aluminium spacer), consequently all the others were compared to these two solutions and assigned with a number from 0 (worst) to 10 (best).

Considering the average rating the best design solution is the TWIST, followed by the HYP&R SikaMove, while the worst design option as far as the U-values are concerned, is the WING. Anyway, it needs to be noticed, that the simplified convective heat transfer model used in the FEM software for the closed cavity of the TWIST frame, could lead to overestimated thermal performances.

Regarding the condensation risk assessment three configuration were considered: adopting steel spacer, TPS spacer and finally a configuration considering a protective layer (silicon or similar) on the uncover glass area between two panels (see Figure 8.2). 0 was assigned to the design options that presented the lowest surface temperature below the dew point threshold (13.2°C), while 1 was assigned if the dew point temperature was overcome. Even adopting a TPS spacer, TWIST is the only option among the S+G designs where the condensation does not occur. All the reference design options do not present condensation risk also employing a steel spacer.

As far as the solar radiation is concerned, only one design option was simulated (HYP&R SikaMove) ad considered to be the weakest under this point of view. In this case it was found that the suggested limit of maximum temperature in the primary sealant (60°C) was overcome during the worst case
scenario conditions. For this reason a 0 (fail) was assigned to the HYP&R Sika as well as to the TWIST design option considering the similar frame width. The rate 1 (pass) was assign to the other design options with a thinner frame. This was considered because the solar radiation effect (raising temperature in the DGU primary sealant) has a minor impact as the width of the frame decreases. Indeed the incident solar radiation component defined as S4 in section 7.3 (Figure 7.4), corresponds to the frame width and is found to be an influent component as due to the frame opacity there is no transmission of the radiation.

Given that the weakness of the S+G design options was found in the condensation risk assessment, a possible improvement on the design would be the introduction of a gasket (or silicone) as protection of the uncovered glass area in the connection between two panels (Figure 8.2). This relatively simple solution can be implemented during the installation of the unitised cells and will lead to a sensibly reduction of the condensation risk increasing the local surface temperatures as already simulated in section 5.6.

Figure 8.2 - Employment of a protection gasket to protect the uncovered glass surface between two panels
8.1 Future work

Building energy performance modelling
The effect of the novel steel-glass composite systems on the energy performance of buildings should be investigated. This can be achieved by performing a 3-dimensional dynamic energy performance simulation using Energy Plus or COMFEN software. This will enable to quantify the lighting and heating/cooling demands on typical buildings with the proposed composite system and will allow direct energy performance comparisons to be made between the proposed system and the conventional CW glazing system.

The numerical model can be extended to a 3-dimensional dynamic energy performance analysis of buildings with different orientations, window-to-wall ratios and geographical locations. It can be possible to investigate the use of high performance glazing technologies in the steel-glass composite system such as building-integrated photovoltaic, vacuum insulation glazing, chromogenic devices and spectrally selective coatings. For these other options a preliminary FEM analysis is needed to evaluate the $\Psi$-value of the new systems, anyway this is beyond the project aims.

Energy design guidelines
As possible outcome of the work, user-friendly energy performance guidelines and selection charts can be developed. These will enable end-users (designers adopting manufactured solution of S+G detail in buildings) of the steel-glass composite systems to select optimal (low energy) configurations of the system, based on building orientation, geographical location, etc. without having to rely on laborious dynamic thermal analysis and optimisation. This can be particularly useful during the early design stages of a building project.
9. CONCLUSIONS

The current work focused on the different aspects of the thermal performance of CW systems (i.e. U-values, surface temperatures, condensation risk etc...) in order to achieve higher performance of the curtain wall system, meeting the objectives of lowering energy demand, improving durability and enhancing comfort. In order to increase the overall thermal performance of curtain walls the following aspects were addressed:

- Low U-values of the whole module and therefore the removal of thermal bridges between glass and supporting structure;
- Relatively high internal surface temperature in order to avoid condensation and the possibility of draft risk, otherwise leading to a decreasing comfort level of the occupants;
- Appropriate temperature of the frame components, as an increasing temperature can compromise performance and durability of some of the components such as the adhesives;
- Control of the differential thermal deformation that can occur between frame and glass.

Novel designs of curtain wall connection were analysed and their thermal performance were studied by means of experimental analysis (climatic cell) and FEM analysis (THERM software). The purpose of the experimental analysis was the verification of the effective improvement of the performance in the new studied details and the comparison with the simulation.

Thanks to the climatic cell located in Turin (kindly offered by TEBE research group, headed by Prof. Marco Perino), the evaluation of the thermal performance of the specimens was done by qualitatively and quantitatively characterizing the thermal bridge effect and its area of influence. To quantify the $\Psi$-value two methods were adopted: a heat flux meter method (HFM) and a thermographic method by means of an infrared camera (IR).

Connected to the FEM analysis, some optimisation of materials selection and design were proposed such as better performing spacer or employment of sealant/gasket to avoid condensation risk. Indeed it was found that the $\Psi$-value can be reduced up to 50% by using a thermoplastic spacer instead of a common aluminium spacer. The studied designs resulted poor performing as far as the condensation risk was concerned. For this reason further improvement of the design is needed in order to increase the surface temperature of the area in the connection between two panels.

Further study will investigate the effect of these novel steel-glass composite systems on the total energy performance of buildings, for some specific case studies.
BIBLIOGRAPHY


ANNEX 1: Experimental set-up of the climatic cell in Turin

**Thermocouples:**

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Infrared Camera:

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<td>IR Camera</td>
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Figure A.1 – Plan view of the climatic cell

Figure A.2 – Section B-B’
ANNEX 1: Experimental set-up of the climatic cell in Turin

Figure A.3 – Section C-C'

Figure A.4 – Section C-C'
## ANNEX 2: Climatic boundary conditions for CW thermal load worst case scenario

### Rome, London and Helsinki locations at 90° tilt:

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<td>°C</td>
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101
Rome, London and Helsinki locations at 0° tilt:

|       | Rome | |       | London | |       | Helsinki |
|-------|------|------|-------|--------|------|--------|
|       | I    | Tair | T sol-air max | I    | Tair | T sol-air max | I    | Tair | T sol-air max |
| January | 452 | 11.4 | 15.33 | January | 271 | 6.90 | 9.26 | January | 118 | -2.80 | -1.77 |
| February | 571 | 12.6 | 17.57 | February | 398 | 7.60 | 11.06 | February | 286 | -4.30 | -1.81 |
| March | 740 | 16.1 | 22.55 | March | 545 | 10.00 | 14.74 | March | 482 | -0.80 | 3.39 |
| April | 839 | 18.8 | 26.10 | April | 735 | 13.10 | 19.49 | April | 664 | 3.80 | 9.57 |
| May | 936 | 23.4 | 31.54 | May | 851 | 15.70 | 23.10 | May | 788 | 8.60 | 15.45 |
| June | 958 | 27.4 | 35.73 | June | 847 | 18.90 | 26.27 | June | 835 | 13.70 | 20.96 |
| July | 909 | 30.4 | 38.70 | July | 807 | 20.80 | 27.82 | July | 804 | 18.50 | 25.49 |
| August | 861 | 30.6 | 38.09 | August | 741 | 20.50 | 26.94 | August | 689 | 17.80 | 23.79 |
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